Space Weather Effects on Radio Propagation: Development of Improved Techniques for the Operation and Analysis of Data for Over-the-Horizon Radar (OTHR)

2023–2024 Mid-Year Report

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Contractor Document Number: TPA 03-2023
Memorandum of Understanding: NRCan Space Weather Effects on DND Assets and Operations
Technical Authority: Thayananathan Thayaparan, Defence Scientist
Contractor's Date of Publication: November 2023

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Abstract

High frequency (HF) radio waves can propagate up to thousands of kilometres via reflections between the ground and the ionosphere. This property of HF radio is used by over-the-horizon radar (OTHR) for long-distance surveillance. However, space weather phenomena can impede the operation of OTHR in different ways. For example, horizontal electron density gradients in the F-region ionosphere can deflect radio waves to off-great circle paths, leading to errors in positioning, while enhanced D-region electron density can cause increased absorption of HF radio waves, reducing the range of frequencies usable by OTHR. It is important that space weather impacts to HF radio wave propagation are understood, so that impacts to OTHR can be mitigated as much as possible.

This report summarizes work done in the first half of the 2023-2024 fiscal year toward better understanding space weather impacts to HF radio wave propagation. Research into off-great circle propagation statistics in the polar cap, diurnal off-great circle propagation caused by the solar-terminator, and the frequency dependence of D-region absorption is described. Then, the installation of a re-built HF transmitter at Resolute Bay, Canada meant to help monitor HF radio wave propagation conditions is described.

Significance for Defence and Security

Over-The-Horizon Radar (OTHR) is sensitive to ionospheric disturbances caused by space weather. Research described in this work aims to improve current OTHR techniques through the development and modification of existing software, and the study of the impact of ionospheric phenomena on HF radio wave propagation used for OTHR.
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Acknowledgements

Dr. Michael Warrington and Dr. Alan Stocker at Leicester University were the original designers of the HF transmitter / receiver equipment and associated software and developed the HIPLAB ray-tracing model. They provided invaluable insight into the operation of the system and ray-tracing model. Infrastructure funding for CHAIN was provided by the Canada Foundation for Innovation (CFI) and the New Brunswick Innovation Foundation (NBIF). CHAIN and its operation are conducted in collaboration with the Canadian Space Agency (CSA). E-CHAIM is supported under Defence Research and Development Canada contract number W7714-186507/001/SS and is maintained by the Canadian High Arctic Ionospheric Network (CHAIN)

This section contains an in-progress paper intended for submission to AGU Radio Science titled “Statistical Analysis of Off-Great Circle Radio Wave Propagation in the Polar Cap” with the following authors: T. G. Cameron, R. A. D. Fiori, G. W. Perry, A. Spicher, and T. Thayaparan. The paper describes a statistical analysis of off-great circle deflections experienced by a polar cap HF radio link.

1.1. Introduction

High frequency (HF) radio waves are frequently used for communications, surveillance, and ionospheric research at high latitudes. The deflection of HF radio waves to off-great circle paths can be problematic for these technologies. Reception of the same signal from different propagation paths can lead to multipath errors, degrading received signal quality. Off-great circle propagation is an important consideration for Over-the-Horizon Radars (OTHRs), which use HF radio frequencies for long-range surveillance (Riddolls, 2006; Thayaparan et al., 2018). OTHRs require detailed knowledge of the propagation paths available to reach a surveillance target, and the deflection of signals to off-great circle paths can lead to significant errors locating these targets.

HF radio waves can be deflected to off-great circle paths by horizontal gradients in ionospheric electron density. Early research focused on systematic deflections of radio waves caused by the solar terminator. Ross and Bramley (1947) reported deflections of up to 20° near sunrise for an approximately 400 km north-south HF radio link. These systematic deflections were periodically reported on in the latter half of the 20th century (e.g., Burtnyk et al., 1962; Morgan, 1974; Tedd et al., 1985). In these studies, the horizontal electron density gradients causing the deflections were frequently characterized as a wrinkling, or tilting of the ionosphere. More recently, focus has shifted to larger deflections caused by localized ionospheric electron density structures, rather than systematic ionospheric tilts. Warrington et al. (1997) reported azimuthal deflections of up to 100° from the great circle direction for HF transmitter links between a transmitter in Alert, Canada, and receivers in Thule, Greenland; Halifax, Canada; and Iqaluit, Canada. These deflections took the form of repeated, monotonic “swings” about the expected azimuthal angle of arrival. They were attributed to reflections off of polar cap density structures, such as polar cap patches and polar cap arcs, and were shown to be consistent with moving reflecting surfaces following ionospheric convection (Warrington et al., 1997).

Polar cap patches are drifting plasma density enhancements found in the polar cap at F-region altitudes (Hosokawa et al., 2019, and references therein) typically when the z-component of the interplanetary magnetic field (IMF $B_z$) is negative. Patches are operationally defined to have peak electron densities that are twice the background density (Crowley, 1996), range from 100 to 1000 km in diameter (Coley & Heelis, 1995), come in a variety of shapes, and appear most often during local winter in the Northern Hemisphere (Coley & Heelis, 1998; Spicher et al., 2017; Noja et al., 2013; Chartier et al., 2018). Patches generally drift anti-sunward across the polar cap with ionospheric convection, though non-zero IMF $B_y$ is also known to result in dawn-dusk motion. A
A statistical study of drift speeds showed that patch drift speeds range up to 500 km/s (Hosokawa et al., 2009), however, faster speeds have been measured (e.g. Weber et al., 1984). Patches were first detected with ionosondes by Meek (1949), though they were not studied frequently until Weber and Buchau (1981) observed patches with all-sky imagers. They have also been investigated with in-situ measurements (e.g. Kivanç & Heelis, 1997; Goodwin et al., 2015; Spicher et al., 2015) and incoherent scatter radars (e.g. Oksavik et al., 2006; Dahlgren et al., 2012; Perry & St.-Maurice, 2018; Jin et al., 2019).

Polar cap arcs are a kind of sun-aligned auroral arc that appear in the polar cap mainly during times of positive IMF $B_z$ (Berkey et al., 1976; Valladares et al., 1994; Hosokawa et al., 2020). They can appear anywhere in the polar cap with a variety of lengths and intensities, sometimes even stretching across the entire polar cap. Typically, larger and brighter arcs are referred to as “transpolar” arcs, while smaller scale, dimmer arcs are called “sun aligned” arcs (Hosokawa et al., 2020). Polar cap arcs predominately form in the evening sector when IMF $B_y > 0$, and in the morning sector when IMF $B_y < 0$ (Fear & Milan, 2012). Once formed, they tend to move towards dusk when IMF $B_y > 0$, and towards dawn when IMF $B_y < 0$ at speeds of a few hundred m/s (Valladares et al., 1994; Hosokawa et al., 2011). As auroral arcs are comprised of precipitating energetic particles, they are also associated with ionospheric electron density enhancements. Some global navigation satellite system (GNSS) total electron content (TEC) measurements of polar cap arcs showed increased electron densities equivalent to up to 7 MHz in critical frequency (Jayachandran, Hosokawa, et al., 2009; Jayachandran et al., 2012). The height of the bottom of these electron density enhancements were seen at altitudes ranging from 110 to 300 km, likely depending on the energy of the precipitating particles.

HF radio wave deflection by polar cap ionospheric density structures is an important consideration for radio propagation models. Warrington (1998) compared an entirely polar cap propagation path to one in which the reflection point was in the auroral zone. They found the polar cap path resulted in much greater azimuthal deviations (~35°) than the auroral zone path (~2.5°). Stocker et al. (2013) showed that Doppler spreads for polar cap propagation paths were significantly larger than those measured for sub-auroral paths. Ray tracing methods have been used to better understand how polar cap patches divert HF radio waves to off-great circle paths. For example, Zaalov et al. (2003) compared measurements of off-great circle propagation due to polar cap patches and arcs to ray tracing simulations of propagation through a model ionosphere with added model patches and arcs. They found the simulations were able to reproduce the character of the observations, suggesting that ray traces could be used to investigate propagation where observations are not available. The development of the ray tracing model, as well as the model ionosphere and patches is further explained in Zaalov et al. (2005). Warrington et al. (2012) presented coverage estimates for high latitude HF radio propagation derived from ray tracing simulations, including how the presence of polar cap patches affects HF radio coverage. OTHR sensitivity to electron density structures has also led to research on how polar cap electron density enhancements could affect OTHR operation. Thayaparan et al. (2020, 2021) used an improved version of the model presented in Zaalov et al. (2005) to demonstrate how polar cap patches could lead to dramatic changes in expected OTHR coverage and ground range.
While previous work shows examples of patch-affected propagation, and quantified the magnitude of possible deviations from the great-circle path, a comprehensive study of off-great circle propagation in the polar cap has not been performed. In this study, nearly 2.5 years of data taken between 2012 and 2016 from a polar cap HF radio link are used to evaluate both the occurrence of off-great circle propagation in the polar cap, and how off-great circle propagation affects HF radio signal properties. Section 1.2 describes the instrumentation and data. Section 1.3 presents an example of off-great circle propagation caused by polar cap patches occurring over a typical day. This is meant to establish that these deflections are due to polar cap ionospheric density structures, and show how deflections and other signal parameters vary with time. A statistical analysis of the HF radio link data set is performed in Section 1.4. The occurrence of off-great circle propagation is explored overall, in terms of time of day and time of year. The dependence of other HF radio signal parameters on deflection from the great circle is explored. Section 1.5 discusses how these results relate to HF radio interactions with polar cap patches and arcs, and possible implications for HF radio technologies in the polar cap.

1.2. Instrumentation and Data

This study uses data from a 577 km HF radio link consisting of a transmitter located in Qaanaaq, Greenland (77.47° N, 69.23° W; QAN) and a receiver located in Alert, Nunavut (82.50° N, 62.35° W; ALE). Qaanaaq and Alert are both located in the polar cap, making this link especially useful for investigating the effects of polar cap ionospheric phenomena on HF radio signals. The Qaanaaq transmitter operated at 100 W and utilized an end-fed V antenna (https://www.bwantennas.com/acs.html) with a directional gain of 0 dB for transmissions. The Alert receiver consists of an array of elevated feed vertical monopoles, connected to an 8 channel direction finding receiver, and is now part of the Natural Resources Canada (NRCan) HF radio network (Cameron et al., 2021). Figure 1.1a shows the location (in geographic coordinates) of the HF radio link relative to the Eureka Canadian High Arctic Ionospheric Network (CHAIN) ionosonde used in the following section. Figure 1.1b shows the location and orientation of the HF radio link at 08:00, 16:00, and 22:00 UT on 07 Nov 2013 relative to the polar cap boundary and a typical anti-sunward, $B_z$-negative flow pattern in geomagnetic coordinates. The anti-sunward flow pattern shown is intended to be illustrative tool, and is not derived from specific measurements or models.
Figure 1.1. (a) Map showing the geographic location of the Qaanaaq HF transmitter, Alert HF receiver, and Eureka CHAIN ionosonde in an orthographic projection. (b) Map in geomagnetic latitude and magnetic local time (MLT) coordinates showing the location and orientation of the Qaanaaq to Alert HF radio link at 08:00, 16:00, and 22:00 UT on 07 Nov 2013 relative to the polar cap boundary (set to 77° magnetic latitude), and to a theoretical anti-sunward, polar cap flow pattern representative of $B_z$-negative, two-cell ionospheric convection.

The QAN transmitter operated by sending 2 seconds long, GNSS time-synchronized signals at each of six distinct frequencies multiple times an hour according to a prearranged schedule. Each transmission was a repeating 13-bit Barker coded signal, which was chosen to be easily identifiable from background noise. The ALE receiver listened for and recorded matching Barker coded signals at the correct frequencies according to the same schedule. Signals were recorded with a bandwidth of 50 kHz, and filtered down to 3 kHz before processing. For each detected transmission, signal parameters including signal-to-noise ratio (SNR), time of flight (TOF), Doppler shift, and Doppler spread were calculated and recorded.

The presence of ionospheric electron density structures in the polar cap make it a complicated propagation environment for HF radio waves. HF radio waves often arrive at the receiver from a multitude of different propagation paths, making it difficult to determine a single set of signal parameters. Accordingly, signal parameters such as the TOF and Doppler shift corresponding to the highest received signal power were calculated and recorded for each transmitted signal. Elevation and azimuthal angle of arrival information were calculated with a direction finding algorithm that compared signal characteristics detected by different antenna elements. Often for low SNR signals, the received signal power is weak enough that the algorithms responsible for calculating signal parameters become dominated by noise, leading to erroneous signal parameters being recorded. This is most common for azimuthal and elevation angle of arrival measurements. In order to minimize the prevalence of erroneous angle of arrival measurements, only signals with SNRs > 0 dB were considered in this study.

This study considers data recorded by the QAN–ALE link between June 2012 and Aug 2016. There were some periods of non-operation during this time due to the remote locations of both the transmitter and receiver. The most notable gap is between Oct 2014
and Feb 2016. Factoring in these periods, the link was operational for 855 days total. The set of frequencies signals were transmitted at, and their accompanying transmission rates changed on 15 December 2013 to accommodate other transmitters. From June 2012 to 15 December 2013, 4.6374, 6.9544, 8.0081, 10.3914, 11.1184, and 14.3644 MHz signals were each transmitted at 30 signals per hour. After 15 December 2013, the 10.3914 MHz transmissions were replaced with 18.3814 MHz transmissions, and transmission rates were reduced to accommodate other transmitters such that 4.6374, 6.9544, 8.0081, 11.1184, 14.3644, and 18.3814 MHz signals were sent at rates of 4, 8, 24, 24, 24, and 8 signals per hour, respectively. For the rest of this study, frequencies are written rounded to one decimal place for brevity. 18.4 MHz signals rarely reached ALE at all, and are not considered in this study. Unfiltered QAN–ALE data recorded from 2012 to 2016 (including SNR < 0 dB and 18.4 MHz signals) can be found at the Harvard Dataverse (https://doi.org/10.7910/DVN/RGDNR1).

1.3. Example of Off-Great Circle Propagation

This section showcases an example of off-great circle propagation caused by polar cap patches, and the effect on received signal parameters. 07 November 2013 was selected as an illustrative example of off-great circle propagation due to signatures in the HF data of polar cap patches crossing the propagation path. Figure 1.2 shows (a) IMF \( B_z \) timeshifted to the magnetopause, (b) the auroral electrojet (AE) index, and the frequency of the F2 layer of the ionosphere (foF2) measured by an ionosonde in (c) Eureka for 07 November 2013. The location of the Eureka ionosonde relative to QAN and ALE is shown in Figure 1.1. Two horizontal blue lines below the x-axis indicate times in which IMF \( B_z \) was negative. IMF \( B_z \) and AE index data was obtained from the OMNI data set (King, 2005; King & Papitashvili, 2020), while Eureka ionosonde data came from CHAIN (Jayachandran, Langley, et al., 2009).
Interplanetary and ionospheric conditions seen throughout the day suggest the presence of polar cap patches. IMF $B_z$ (Figure 1.2a) is primarily negative for the first half of the day, reaching $-12.5$ nT before transitioning to positive at approximately 12:00 UT, and remains positive until 19:00 UT, after which it fluctuates between 0 and $-5$ nT for the rest of the day. The AE index (Figure 1.2b), which is a measure of geomagnetic activity in the auroral zone, is elevated during the periods of negative IMF $B_z$. Polar cap patches are known to appear at times when geomagnetic activity is occurring (Hosokawa et al., 2019).

The foF2 measured in Eureka (Figure 1.2c) varies substantially across the day. The ionosonde measures repeated, 10s of minutes long fluctuations in foF2 concurrent with the periods of negative IMF $B_z$ and elevated AE index. These fluctuations range between 4 and 8.8 MHz during the first period of negative IMF $B_z$, and between 3.6 and 7.6 MHz during the second period. These foF2 fluctuations are consistent with polar cap patches passing over the Eureka ionosonde. The ionospheric electron density during these fluctuations reaches more than twice the background density, consistent with the formal definition of a polar cap patch (Crowley, 1996).
Figure 1.3. Summary plot of HF radio signals for the Qaanaaq to Alert propagation path on 07 November 2013. Panels (a–e) from the top-down show (a) Periods of HF reception of signals at the prescribed frequency, (b) azimuthal angle of arrival, (c) time of flight (TOF), (d) Doppler shift, and (e) Doppler spread across the entire day. Panels (f–j) show a zoomed in view of the same signal parameters from 22:30–23:30 UT. Frequencies recorded are: 4.6 MHz (blue), 7.0 MHz (orange), 8.0 MHz (green), 10.4 MHz (red), 11.1 MHz (purple), 14.4 MHz (brown). Time is indicated by day of month and HH:MM on the bottom x-axis, with the month and year indicated in the lower right. The dashed horizontal lines in (b) and (g) indicate the great circle heading (GCH) from Alert to Qaanaaq. Three vertical dashed lines in panels (a–e) indicate times the orientation of the HF link was shown in the right panel of Figure 1.1. Two periods of negative IMF $B_z$ are indicated with horizontal blue lines, and the zoomed-in period shown in panels (f–j) is indicated by a horizontal red line below the x-axis.

Figure 1.3 shows a selection of recorded parameters for all signals received by the Alert HF radio receiver on 07 November 2013. The panels on the left (a–e) show time series of (a) signal frequency (b) azimuthal angle of arrival, (c) TOF, (d) Doppler shift, and (e) Doppler spread across the entire day. The two periods of negative IMF $B_z$ are indicated by horizontal blue lines below the x-axis. The panels on the right (f–j) show a zoomed-in view of the same signal parameters for 22:30–23:30 UT, intended to illustrate a single patch crossing. This time is indicated with a red horizontal line below the x-axis. Throughout the day, all frequencies except 14.4 MHz arrive consistently at Alert (Figure 1.3a), apart from a period between 14:00 and 20:00 UT, in which reception for 10.4 and 11.1 MHz signals becomes intermittent. This time corresponds to a period of low geomagnetic activity (indicated by IMF $B_z$ and AE in Figure 1.2), and consequently low polar cap patch
occurrence. This suggests that polar cap patches aided in the reception of 10.4 and 11.1 MHz waves outside this period, and that the background ionospheric electron density was too low to consistently reflect these frequencies back toward Alert without the patches.

The great circle heading (GCH) from Alert to Qaanaaq is an azimuthal angle of 196.79°. Deviations from this value indicate off-great circle propagation. During the first period of negative IMF $B_z$ (01:30–12:00 UT), the received azimuth of radio signals at all received frequencies (Figure 1.3b) undergoes repeated “swings”, in which the azimuth repeatedly changes from below the GCH to above the GCH. The azimuthal extent of these swings varies by frequency, such that higher frequencies exhibit larger deflections. Deflections of > 90° from the expected great circle azimuth are observed for the higher frequencies, consistent with previous observations of azimuthal deflections thought to be caused by polar cap patches crossing the propagation path (e.g. Warrington et al., 1997; Zaalov et al., 2003). Additionally, the higher frequency signals (10.4 and 11.1 MHz) during this period are only detected at large deflection angles from the GCH. This is probably because these signals are at too high of a frequency to be reflected back to Alert along the great circle. This is consistent with the relative absence of 10.4 and 11.1 MHz signals during the subsequent Bz-positive period from 12:00 - 19:00 UT. They can only reach Alert along propagation paths with large azimuthal deflections, since these paths interact with the ionosphere and patches at shallower elevation angles.

The swings in azimuth end at 12:00 UT, consistent with IMF $B_z$ transitioning to positive. Geomagnetic activity indicated by the AE index and fluctuations in foF2 also cease soon after. Between 12:00 and 19:00 UT, a large, unstructured spread in azimuthal angle of arrival can be seen at all frequencies. After IMF $B_z$ becomes negative again at 19:00 UT, the azimuthal angle of arrival exhibits azimuthal swings transitioning from approximately the GCH to ~100° below the GCH. Figure 1.3g shows a zoomed in view of a single, especially coherent azimuthal swing likely associated with a polar cap patch. The azimuthal angle of arrival for each received frequency follows the same general curve, varying from above the GCH to below the GCH over the hour, though azimuths measured at the same time for different frequencies do differ by up to 30° at times. This is likely the result of different frequencies reflecting off different parts of the patch, since higher frequencies will penetrate farther.

Other signal parameters exhibit distinct behavior during the two negative IMF $B_z$ periods. During both periods, the TOF at all frequencies (Figure 1.3c) undergoes repeated rises and falls between 2.2 and 6.8 ms that line up with the swings in angle of arrival, such that signals with the largest azimuthal deflections from the GCH also have the highest TOFs. This is not surprising since signals that experience larger azimuthal directions likely also take longer paths to reach Alert. Correspondingly, higher frequencies generally reach larger TOFs, since they also experience larger deflections. The TOFs for all frequencies seen in Figure 1.3h are largest at the beginning and end of the crossing. The TOFs for individual frequencies are clearly stratified according to frequency as well. Referring back to the full interval, from 12:00–19:00 UT when IMF $B_z$ is positive, the TOF at all frequencies undergoes slower and large variations. During this time signals are received with TOFs of up to 8.0 ms, larger than what is seen when IMF $B_z$ is negative.
Doppler shifts (Figure 1.3d) also exhibit “swings” that correspond to swings in azimuthal angle of arrival during the two negative IMF $B_z$ periods. During the first period (01:30–12:00 UT), Doppler shifts repeatedly change from as high as $\sim 30$ Hz to as low as $\sim -25$ Hz. Higher frequency signals generally experience larger positive and negative Doppler shifts. During the second period of negative IMF $B_z$ (18:00–24:00 UT), repeated swings in Doppler shift from 0 Hz to as low as -30 Hz can be seen concurrent with azimuthal angle of arrival swings. Notably, while the azimuthal angle of arrival swings reverse direction between the first and second negative IMF $B_z$ periods, the accompanying Doppler shifts do not. Doppler shifts at all frequencies for the single patch crossing (Figure 1.3i) drop from above to below zero Hz across the interval, lining up with the azimuthal swing. However, swings for different frequencies do not line up. Instead, the slope of the swings in Doppler shift get larger with increasing frequency.

Doppler spread (Figure 1.3e) is a measure of the size of the range of Doppler shifts a given HF radio signal was received at. Doppler spread for all frequencies varies between 0 and 20 Hz from 00:00 UT until midway into the first negative IMF $B_z$ period at 04:30 UT. At 04:30 to 12:00 UT, larger variations in Doppler spread of up to 65 Hz can be seen at all frequencies. 04:30 UT is approximately the time when the AE index (Figure 1.2b) becomes elevated past 250 nT. For the rest of the day, Doppler spread varies again between 0 and 20 Hz at all frequencies. There is a small population of isolated 10.4 and 11.1 MHz signals with Doppler spreads between 45 and 65 Hz during the second period of negative IMF $B_z$. Doppler spreads measured for the single, clear patch crossing during this period (Figure 1.3j) are generally low. This contrasts with the increased Doppler spreads seen for other patch crossings. It could be that the patch responsible for the swing from 22:30–23:30 UT contained less internal structuring. Simpler internal structuring would result in smaller Doppler spreads since there would be less variation in the Doppler shift experienced by a single transmission. It is also consistent with the reduced scatter in azimuthal angle of arrival compared to the first interval, since a spatially simpler patch would reflect HF radio waves in a more consistent way.

1.4. Statistical Analysis

1.4.1. Occurrence and Magnitude of Off-Great Circle Deflections

A complete year of Qaanaaq to Alert transmissions from April 2013 to April 2014 was used to study the occurrence and magnitude of off-great circle propagation in the polar cap. This period represents the most consistent 1-year interval of data collection, allowing examination of the data without seasonal bias. It should be noted that this period occurred during solar maximum, and therefore observes higher geomagnetic activity, and is expected to observe a higher occurrence of polar cap density structures than in surrounding years. Additionally, the data only represents transmitted signals that actually reached and were detected by the receiver. This does not include signals that experienced too much absorption to reach Alert, signals that escaped to space, or signals that never reached the receiver due to azimuthal deflections.

Figure 1.4 shows normalized histograms with 2° bins representing the distribution of deflections from the GCH for all received QAN–ALE HF radio signals from 01 April 2013 to 01 April 2014. Since the transmission rates for all frequencies changed in December
2013, deflections were weighted by the inverse of the transmission rate to ensure all parts of the year were represented equally in time. The histograms were also normalized to ensure the sum across all bins is 1. From the top down, panels show distributions for (a) 4.6 MHz, (b) 7.0 MHz, (c) 8.0 MHz, (d) 11.1 MHz, and (e) 14.4 MHz. The distribution for 10.4 MHz is omitted since the frequency was not transmitted for the entire year. The vertical axis range cuts off the strong peak observed in all distributions at 0° deflection to emphasize the features away from the great-circle heading. All distributions show significant populations of deflections that are distinct from the peak at 0°. The distribution for 4.6 MHz has a distinct population that peaks at −22° deflection. Distributions for frequencies > 4.6 MHz contain sizable populations of positive and negative deflections, that increase in relative size with increasing frequency up to 11.1 MHz. The distribution for 14.4 MHz contains a smaller sized population of deflections (>30°) compared to 11.1 MHz. Since considerably fewer signals were received at 14.4 MHz compared to the other frequencies, some discrepancies at 14.4 MHz may be due to the smaller sample size.

At the higher frequencies, these populations of deflections have distinct positive and negative peaks. For example, the distribution for 11.1 MHz (panel d) has localized west and east peaks at approximately −70° and 60° from the GCH. At frequencies ≥ 11.1 MHz, there are local minima at approximately ±30° deflection, where the decreasing on great circle population meets the increasing off-great circle population. This minimum can also be seen for negative deflections in the 8.0 MHz distribution. Dashed vertical lines at ±30° show this transition point in each panel. On average over the year, received 4.6, 7.0, 8.0, 11.1, and 14.4 MHz signals had deflections larger than 30° 15.9%, 32.1%, 45.1%, 65.6%, and 38.1% of the time, respectively. These distributions are also asymmetric. More signals arrive with negative deflections than positive deflections for all frequencies, which corresponds to more signals arriving from east of the great circle heading than west. Again averaged over the year, received 4.6, 7.0, 8.0, 11.1, and 14.4 MHz signals arrived from the east of the GCH 61.2%, 59.8%, 56.6%, 55.9%, and 58.5% of the time, respectively.

These results were determined from an analysis of individually received signals and their accompanying deflections. However, for operation of HF radio technology at high latitudes, it may be more useful to understand what percentage of transmitted signals can be expected to be deflected to off-great circle paths, rather than the percentage of received signals. To do this, the number of hour-long intervals in which the median magnitude of deflection from the GCH was larger than 30° was compared to the total number of intervals for which the QAN–ALE link was operational. The percentage of intervals where the median deflection was >30° was 11.8%, 29.1%, 43.1%, 36.1%, and 9.6% for the 4.6, 7.0, 8.0, 11.1, and 14.4 MHz frequencies, respectively, for the April 2013 to April 2014 period considered. The drop in percentage for the higher frequencies is due to the much lower number of signals received compared to the lower frequencies. Due to the short length of the QAN–ALE path, high frequency signals are more likely to escape to space.
Figure 1.4. Normalized distributions of deflection from the great circle heading for all signals received at Alert from Qaanaaq from 01 April 2013 to 01 April 2014. Panels show distributions for (a) 4.6 MHz, (b) 7.0 MHz, (c) 8.0 MHz, (d) 11.1 MHz, (e) 14.4 MHz. Vertical dashed lines in each panel indicate ±30°, and the vertical dotted line indicates 0°. The y-axis range in each panel was chosen to focus on the distribution away from the great circle heading. The percentage of received signals with deflections > 30°, the total number of signals received, and the peak distribution density are reported in the top right of each panel. Deflections were weighted by the inverse of transmission rate to ensure all parts of the year were represented equally.

Since the occurrence of polar cap density enhancements thought to be responsible for signal deflections vary significantly with season and time of day, it is useful to explore how deflections from the GCH also vary with time. To investigate how the magnitude of off-great circle deflections changed over the year, the median magnitude of deflection from the GCH was calculated for signals received during each week from 01 April 2013 to 01 April 2014, for each frequency. Week-long bins were chosen to smooth out day-to-day variability caused by changing geomagnetic activity, while still preserving variation on
longer time scales. Figure 1.5a shows this weekly median deflection for (blue) 4.6, (orange) 7.0, (green) 8.0, and (purple) 11.1 MHz. 14.4 MHz signals were omitted because too few signals were received per week to calculate consistent weekly medians. Weeks for which less than 10% of transmitted signals were received were also omitted on a per frequency basis for the same reason. The shaded region in the figure indicates local winter (between the fall and spring equinoxes).

The median weekly deflection for all frequencies reach minimum and maximum values near the summer and winter solstice, respectively. Median weekly deflections for all frequencies during the summer are especially close to zero. Comparing different frequencies, median weekly deflection generally increases with increasing frequency. This relationship can be seen throughout the year, though the median daily deflection for 7.0, 8.0, and 11.1 MHz reaches a consistent maximum near the winter solstice. Median daily deflection reaches ~30° on average for 4.6 MHz, and ~50° on average for 7.0, 8.0, and 11.1 MHz in the winter months. During the first week of 2014, the weekly median deflection for 11.1 MHz temporarily drops to close to zero.

Figure 1.5b shows a scatter plot of individual deflections experienced by 11.1 MHz signals across the same time period as panel (a). Overlaid are weekly medians for just positive and negative 11.1 MHz deflections. Comparing the individual deflections to the medians,
changes in the weekly median deflection seem to be due to changes in the occurrence of large deflections compared to on-great circle signals, rather than changes in the magnitude of the off-great circle deflections. During the summer, the occurrence of 11.1 MHz off-great circle deflections is close to zero, while large deflections are extremely common in the winter. The occurrence of received 11.1 MHz signals is lower near the winter solstice, likely because polar cap ionospheric electron density is consistently low at the time due to the lack of solar photoionization.

To investigate how deflections from the GCH varied across the day, received signals were binned by time of day (UT) in 2-hour increments and day of year in 21-day increments, and the median magnitude of deflection from the GCH was calculated for each bin from 01 April 2013 to 01 April 2014. As with Figure 1.5, bin sizes were chosen to ensure enough signals fell in each bin to calculate consistent medians while still showing changes across the day and year.

Figure 1.6. Median magnitude of deflection from the GCH from 01 April 2013 to 01 April 2014 for HF radio signals binned by time of day (UT) in 2-hour increments and day of year in 21 day increments for (a) 4.6, (b) 7.0, (c) 8.0, (d) 11.1, and (e) 14.4 MHz signals. Medians were not calculated for bins containing < 10 received signals, and those bins are marked white. Solid white lines indicate the winter and summer solstices and dashed white lines indicate the spring and fall equinoxes.
Figure 1.6 shows the median magnitude of deflection from the GCH versus time of day and day of year for (a) 4.6, (b) 7.0, (c) 8.0, (d) 11.1, and (e) 14.4 MHz signals. The solstices and equinoxes are marked with solid and dashed white vertical lines, respectively. The majority of deflections for all frequencies occur in local winter. How median deflection varies across the day clearly changes with both frequency and time of year. During the winter months, for the lower three frequencies, the median magnitude of deflection peaks in the UT morning, and the duration of the day for which large deflections occur gets wider with increasing frequency. For instance, the median magnitude of deflection is $> 45^\circ$ from 10:00 to 12:00 UT for 4.6 MHz, from 00:00–16:00 UT for 7.0 MHz, and from 00:00–18:00 UT and 22:00–24:00 UT for 8.0 MHz. During summer months only the 8.0 MHz signal experiences significant deflections, with a peak at ~06 UT.

The distribution of median deflection with respect to time of day and day of year for the two higher frequencies is noisy due to the relatively lower number of received signals, especially 14.4 MHz. However, there are clear differences in the variation of median deflection across the day when compared to the lower frequencies. Focusing on 11.1 MHz, median deflection near the beginning and end of local winter is high across the day and largest in the morning, matching the lower frequencies. Near the winter solstice however (from roughly mid-November to mid-January), the median magnitude of deflection is close to zero from 02:00 and 14:00 UT, and almost entirely $> 50^\circ$ after 14:00 UT and before 02:00 UT. While there is more noise due to the lower number of received signals, the median deflection distribution for 14.4 MHz signals generally agrees with the pattern for 11.1 MHz, except that large deflections are only detected from 18:00–22:00 UT near the winter solstice.

1.4.2. Effects of Off-Great Circle Propagation on HF Radio Signal Parameters

This section examines how off-great circle propagation affects other relevant HF radio signal characteristics. From the set of all signals received during local winter (between the fall and spring equinoxes) between June 2012 and August 2016, 2D histograms of signal deflections from the GCH and a selection of relevant HF radio properties for each of six frequencies (4.6, 7.0, 8.0, 10.4, 11.1, and 14.4 MHz) were generated. The counts in these histograms were converted to 2D discrete distribution densities so that the sum over all bins, multiplied by the bin widths would be 1. To focus on off-great circle signals, which were shown in Fig. 5 to be much more common in winter, only local winter signals were considered.

Figure 1.7 shows the discrete distribution density of local winter signals versus TOF (0.2 ms bins) and deflection from the GCH (8 bins) for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, and (f) 14.4 MHz. The range of TOFs seen for all frequencies has a hard cutoff which is consistent with the 1.91 ms on-great circle speed of light travel time between QAN and ALE. The range of signal deflections extends from $-180^\circ$ to $180^\circ$. All frequencies show two distinct populations. Closest to the 1.91 ms lower cutoff, there is a population of largely on-great circle signals separated in TOF from the rest of the distribution for all frequencies. This population has a limited extent in deflection that increases with increasing frequency. At the higher frequencies (10.4–14.4 MHz), increasing deflection does lead to a small increase in the TOF. The TOF associated with the peak of this part of the distribution is
consistent with the TOF expected for on-great circle propagation from QAN–ALE, with a single reflection off the E region (∼100 km altitude).

Figure 1.7. Discrete distribution density of received signals versus time-of-flight and deflection from the great circle heading for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, (f) 14.4 MHz. All distributions are plotted with a logarithmic color scale to better highlight off-great circle signals. Only radio signals received during local winter (between fall and spring equinoxes) were considered. Zero deflection is indicated by a vertical white dashed line. The red and light blue overlaid curves show the expected time of flight assuming radio waves reflected off patches crossing halfway between Qaanaaq and Alert at 300 and 100 km altitude respectively.

The rest of the TOF range is represented by a population of signals with TOFs ranging from 2.4 ms to up to 10 ms, with deflections ranging from −180° to 180°. This population is very similar at all frequencies, except for 4.6 MHz, for which the range of TOFs is reduced. At all frequencies, signals with larger deflections tend to also have larger TOFs. The
population also shows a spreading in the off-great circle part of the distribution, such that signals with increasingly larger TOFs have a larger range of possible deflections. The TOF associated with the on-great circle part of this population is consistent with on-great circle propagation from QAN–ALE with a single reflection off the F-region (300 km).

Figure 1.8 shows the discrete distribution density of local winter signals versus Doppler shift (1.5 Hz bins) and deflection from the GCH (8° bins). At all frequencies, the peak distribution density occurs for zero Doppler shift and zero deflection from the GCH. Away from zero deflection, all frequency distributions are largely symmetric with respect to Doppler shift and deflection. All frequencies show a pattern in which larger deflections from the GCH up to 90° yield a larger possible range of positive and negative Doppler shifts. This range also increases with increasing frequency. For deflections larger than ±90°, the distribution density tapers off such that the largest deflections tend to have Doppler shifts closer to zero. The 4.6 MHz distribution shows an asymmetry in which negative azimuthal deflections lead to a larger range of Doppler shifts than positive deflections. This may be related again to the relatively small number of off-great circle 4.6 MHz signals when compared to the other frequencies.

Figure 1.9 shows the discrete distribution density of local winter signals versus Doppler spread (1 Hz bins) and deflection from the great circle heading (8° bins) for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, and (f) 14.4 MHz. Similar to Doppler shift, the peak distribution density occurs at zero Doppler spread and zero deflection from the GCH for all frequencies. Signals with higher Doppler spreads are observed at all frequencies primarily at non-zero deflection angles from the GCH. These high Doppler spread signals generally fall in two bands, one at positive deflection angles, and one at negative deflection angles. The width and horizontal location of these bands likely just indicate the deflection angles most off-great circle signals arrived at (also seen in Figure 1.4). The range of Doppler spreads with appreciable distribution density increases with frequency up to 11.1 MHz, with the range for 14.4 MHz somewhat lessened. Doppler spreads of up to ∼24 Hz are observed at 4.6 MHz, while Doppler spreads of up to ∼35 dB are observed at 11.1 MHz. Similar to Figure 1.8, 4.6 MHz signals with negative deflections are seen to lead to larger Doppler spreads than signals with positive deflections.

Figure 1.10 shows the discrete distribution density of local winter signals versus SNR (1.0 dB bins) and deflection from the GCH (8° bins) for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, and (f) 14.4 MHz. All frequencies show a peak in distribution density at close to zero deflection. This peak extends from 30 to 35 dB SNR for 4.6 to 8.0 MHz, while it is much more tightly focused around 35 dB for 10.4 to 14.4 MHz. For deflections away from zero, the distribution density at all frequencies is lower, and ranges in SNR from 0 to approximately 35 dB. The 4.6 MHz distribution is an exception to this pattern, where appreciable distribution density only reaches as low as approximately 10 dB for off-great circle signals. This is probably due to the comparative low number of off-great circle signals received at 4.6 MHz compared to the other frequencies (seen in Figure 1.4).

Focusing on SNR <25 dB for the higher five frequencies, there is appreciable distribution density in three distinct bands extending downwards in SNR to -15 dB. These bands are separated by relative gaps in distribution density. One 10° wide band is centered around
zero deflection, with more distribution density negative of zero. The other two bands span approximately $-150^\circ$ to $-45^\circ$, and $30^\circ$ to $100^\circ$ in deflection from the GCH, though they widen slightly with decreasing SNR. The negative deflection band is generally wider than the positive deflection band at all frequencies.

**Figure 1.8.** Discrete distribution density of received signals versus Doppler shift and deflection from the great circle heading for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, (f) 14.4 MHz. All distributions are plotted with a logarithmic color scale to better highlight off-great circle signals. Only radio signals received during local winter (between fall and spring equinoxes) were counted. Zero deflection is indicated by a vertical white dashed line, and the red overlaid curves show the expected Doppler shift assuming radio waves reflected off patches crossing halfway between Qaanaaq and Alert at 300 km altitude.
Figure 1.9. Discrete distribution density of received signals versus Doppler spread and deflection from the great circle heading for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, (f) 14.4 MHz. All distributions are plotted with a logarithmic color scale to better highlight off-great circle signals. Only radio signals received during local winter were counted. Zero deflection is indicated by a vertical white dashed line.
Figure 1.10. Discrete distribution density of received signals versus SNR and deflection from the great circle heading for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, (f) 14.4 MHz. All distributions are plotted with a logarithmic color scale to better highlight off-great circle signals. Only radio signals received during local winter were counted. Zero deflection is indicated by a vertical white dashed line.

Because there is comparable distribution density for on and off-great circle signals at low SNR, it is hard to tell from Figure 1.10 if off-great circle signals tend have low SNR more often than on-great circle signals. It is possible that they do, but the generally higher occurrence of on-great circle signals leads to similar occurrence frequencies. To untangle this, the pointwise mutual information (PMI) between SNR and deflection from the GCH can be calculated (Lizier, 2014). PMI is defined as

$$\text{PMI}(x;y) = \log_2 \left( \frac{p(x,y)}{p(x)p(y)} \right),$$

(1)
where \( p(x) \) and \( p(y) \) refer to the probability distributions of the random variables \( X \) and \( Y \) respectively, and \( p(x,y) \) is the joint probability distribution of \( X \) and \( Y \). PMI quantifies whether specific values of \( x \) and \( y \) occur together more or less often than would be expected if their distributions were independent, such that a PMI of \( n \) bits means the corresponding \( x \) and \( y \) values occur together \( 2^n \) times as often. In this case, \( p(x) \) and \( p(y) \) are approximated with 1D histograms of deflection and SNR respectively, while \( p(x,y) \) is approximated with the 2D histogram of both. Cameron et al. (2019) contains a more detailed explanation of PMI, as well as a few illustrative examples of its utility.

Figure 1.11 shows the PMI between SNR and deflection from the great circle heading for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, and (f) 14.4 MHz. The histograms used to calculate PMI used the same bin widths as Figure 1.10. At every frequency, the PMI shows that off-great circle signals are much more likely to have SNR < 30 dB, while on-great circle signals are much less likely to have SNR < 30 dB. The apparently high distribution density of low SNR, on-great circle signals is simply because so many more on-great circle signals were recorded than off-great signals. Interestingly, the PMI for SNR > 30 dB is highest for deflections between \(-45^\circ\) and \(45^\circ\), with a clear gap at \(0^\circ\). This suggests that the signals with the highest SNR experienced non-zero deflections of less than \(45^\circ\) more often than expected.

1.5. Discussion

In this study, off-great circle propagation in the polar cap was studied using nearly 2.5 years of data from a polar cap HF radio link. An example of a day of patch affected HF propagation was presented in Section 1.3. Repeated \(\sim30–60\) minute long swings in the azimuthal angle of arrival occurred in two periods during the day when IMF \(B_z\) was negative. These swings were attributed to polar cap patches crossing the propagation path. As each patch approached, crossed, and then receded from the propagation path, the azimuthal angles of radio waves that reflected off the patch and reached the receiver changed smoothly from one side of the GCH to the other.

The orientation of the azimuthal swings reversed for patches observed 01:30–12:00 UT and 18:00–24:00 UT, which can be explained by the rotation of the Earth under the polar cap convection pattern, illustrated in the right panel of Figure 1.1. During the first period, patches moving with ionospheric convection from the dayside to nightside of the Earth crossed the QAN–ALE path from roughly east to west, resulting in azimuthal swings from below to above the GCH (see 08:00 UT in Figure 1.1). During the second period, which was \(\sim12\) hours later, the Earth and the QAN–ALE path had rotated under the convection pattern so that patches crossed from west to east, and the corresponding swings were in the opposite direction (22:00 UT in Figure 1.1).
Figure 1.11. Pointwise mutual information between SNR and deflection from the great circle heading for (a) 4.6, (b) 7.0, (c) 8.0, (d) 10.4, (e) 11.1, (f) 14.4 MHz. Only radio signals received during local winter were counted. Zero deflection is indicated by a vertical black dashed line, and bins with no data are indicated with gray.

The effects these deflections had on other parameters are also consistent with the patch crossings. Signals with larger deflections from the GCH traveled longer paths to reach Alert, leading to larger TOFs. Positive to negative Doppler shift swings are the result of reflection off the moving patches. As a patch approaches perpendicular to the path, the reflected radio waves experience Doppler shifts that get progressively smaller, since the component of the patches’ velocity parallel to the wave propagation direction decreases with the magnitude of deflection. As the patch recedes, the reflected radio waves experience negative Doppler shifts that get progressively larger. This pattern is the same regardless of which side the patches approach from, explaining why the Doppler shifts are
positive to negative during both periods. Increased Doppler spreads may be caused by the interaction of the HF radio waves with spatial structuring associated with patches.

There is an asymmetry in the azimuthal swings (relative to the GCH) and associated Doppler shifts during the beginning of the second negative IMF $B_z$ period that was not seen during the first. This asymmetry may be because the Qaanaaq to Alert path was at an oblique angle relative to the convection flow during this time, affecting both the azimuthal swings and the Doppler shifts. Patches or arcs moving near the propagation path but not directly crossing would lead to partial swings entirely on one side of the GCH, and entirely positive or entirely negative Doppler shifts.

During the period when IMF $B_z$ was positive, less structured deflections were still observed at all frequencies. Accompanying Doppler shifts were generally low and negative during this period. This behavior is also consistent with ionospheric convection. When IMF $B_z$ turns positive, ionospheric convection largely slows, but patches don't immediately disappear. These deflections and accompanying Doppler shifts could be caused by deflections off of decaying, still-moving patches. It is also possible that some deflections during this time are due to interactions with a polar cap arc, since polar cap arcs are associated with positive IMF $B_z$.

In Section 1.4.1, a mostly uninterrupted year of QAN–ALE transmission data was used to quantify the occurrence and magnitude of polar cap off-great circle propagation. The distribution of HF radio signal deflections across the year for 6 frequencies from 4.6–14.4 MHz (Figure 1.4) showed that deflections from the GCH are common, and that the occurrence and magnitude of these deflections increase with frequency up to at least 11.1 MHz. This behavior is consistent with the supposition that polar cap patches and arcs are responsible for these deflections. 4.6 MHz waves are reflected back towards the ground at a lower altitude than higher frequency waves, rarely reaching a high enough altitude to have their trajectories altered by patches or arcs. Higher frequency waves are able to penetrate higher into the ionosphere, and are more likely to interact with patches or arcs. If the wave frequency is too high however, these waves may pass through patches or arcs completely, escaping to space. This may explain the lower occurrence of off-great circle deflections for 14.4 MHz compared to 11.1 MHz. Since polar cap arcs have been known to occur at E-region altitudes, it is possible that lower frequencies are more likely to experience deflections caused by arcs than patches, since patches are primarily F-region phenomena.

Plots of the weekly median magnitude of deflection showed that deflections were largest in the local winter and were close to zero in the summer, for frequencies up to 11.1 MHz. Plots of the median magnitude of deflection signals binned by hour of the day (UT) and day of year showed that deflections for frequencies up to 8.0 MHz peaked in the UT morning (~06:00 UT) across local winter. Deflections for 11.1 MHz signals also peaked in the UT morning at the beginning and end of local winter. Near the winter solstice however, 11.1 MHz median deflections were found to be close to zero from 02:00–14:00 UT, and high (generally > 50°) for the rest of the day. The observation that deflections are highest in the winter months and close to zero in the summer months is consistent with polar cap patch occurrence statistics reported for the Northern Hemisphere by Noja et al. (2013),
Spicher et al. (2017), and Chartier et al. (2018), who all observed that patch occurrence is highest in the winter months and close to zero in the summer months.

Comparison of the observed distribution of off-great circle deflections across the day with patch occurrence statistics requires some care, since more factors than just the occurrence of ionospheric enhancements affect the occurrence of deflections. For a signal to experience a deflection from a patch, the wave frequency must be high enough compared to the background electron density to reach the F-region, but still low enough relative to the patch density that it experiences a deflection instead of escaping to space. Since 11.1 MHz signals experienced deflections more often than the other frequencies, the distribution of 11.1 MHz deflections across the day is most likely to match up with studies of patch occurrence. A study of the occurrence rate of patches using local winter (Jan–Mar and Sep–Dec) observations from the Resolute Bay Incoherent Scatter Radar Canada (RISR-C) (Ren et al., 2018) reported that 60% of patches were observed from 1200 to 2400 MLT (19:00 to 07:00 UT), with the maximum patch occurrence occurring from 21:00 to 02:00 UT. This is approximately consistent with the observed distribution of 11.1 MHz deflections, since deflections were only observed consistently across the entire winter from 14:00 to 02:00 UT and only at the beginning and end of winter at other times.

David et al. (2019) and David et al. (2016) investigated polar cap patch occurrence with respect to UT time and day of year with maps of TEC. In both studies, they found that in the Northern Hemisphere, patches were most common around 00:00–12:00 UT near the spring and fall equinoxes. In the middle of winter however, patch occurrence was close to zero from around 02:00–12:00 UT, and high after 12:00 and before 02:00 UT. Kagawa et al. (2021) observed a similar pattern studying patch occurrence with in-situ plasma density measurements, where patches were most common near the solstice from 15:00–24:00 UT. Results from all three studies match the occurrence of 11.1 MHz deflections well, and all report the same “hole” in patch occurrence near the solstice in the UT morning (e.g. Figure 3 from David et al. (2019)). These studies attribute variation in patch occurrence across the day and year to an explanation of patch formation in which patches are created when high density, sunlit plasma is drawn into the lower density polar cap by the polar cap convection pattern. According to this explanation, patch occurrence is highest during times when most of the polar cap is in darkness, but there is still significant overlap between the solar terminator and the polar cap convection pattern. The “hole” in the winter patch distribution exists because near the winter solstice, polar cap convection can only draw in lower density nightside plasma because the solar terminator is too far south. Figure 4 in David et al. (2019) shows this clearly with patch-to-background ratios calculated from Utah State University Time Dependent Ionospheric Model (TDIM) runs for different times of day and year, based on earlier work by Sojka et al. (1993). This “hole” is also present in climatological observations of TEC irregularities reported by Jin et al. (2022).

The correspondence of 11.1 MHz deflections to patch occurrence with respect to UT and time of year suggests that a significant amount of these deflections are caused by polar cap patches. The distribution of deflections at other frequencies can be compared to patch occurrence as well, given the other factors affecting the occurrence of deflections. The 14.4 MHz distribution of deflections also lines up approximately with the patch distribution whenever enough signals were received to calculate median deflections, except there is a drop in deflections in the UT evening near solstice compared to 11.1 MHz. This could
be because the patch-to-background ratio at this time is expected to be lower than the surrounding weeks (seen in Figure 4 of David et al. (2019)), meaning 14.4 MHz waves are deflected less, but 11.1 MHz waves are not at a high enough frequency to be affected.

The deflection distributions for the lower three frequencies do not show a “hole” in the winter solstice UT morning at all. This difference between the lower and higher frequency UT distributions suggests that the lower frequency deflections at this time are caused by ionospheric electron density enhancements with peak densities too low to deflect 11.1 MHz signals, but still high enough relative to the background density to deflect 8.0 MHz and lower signals. These enhancements could be too low density to be considered patches according to the classical definition (twice the background density), explaining their absence from patch occurrence trends. They could, for example, be the result of plasma ionized by electron precipitation in the auroral region, or simply higher density plasma closer to the solar terminator, being drawn into the polar cap by convection. Some of these low frequency deflections could be due to polar cap arcs as well.

The final part of this study investigated the effect off-great circle deflections have on other signal characteristics. Signals that experienced large positive and negative deflections from the GCH tended to have larger TOFs, a larger range of possible positive and negative Doppler shifts, and larger Doppler spreads. The connection between SNR and deflection from the GCH was hard to untangle from the occurrence of deflections, but an analysis of the PMI between the two showed that signals with larger deflections were more likely to have lower SNRs than what would be expected if the two quantities were independent.

A simple, illustrative model of localized density enhancements crossing the QAN–ALE propagation path can be used to explain the shapes of the TOF - deflection distributions seen in Figure 1.7. These enhancements could be polar cap patches, polar cap arcs, or any other localized electron density structure capable of reflecting HF radio waves. In this model, the QAN–ALE propagation path is aligned along the y axis, and the z direction is corresponds to straight up. A localized electron density enhancement at a height h crosses the QAN–ALE propagation path exactly halfway between the two locations, moving at some velocity v in the x direction. Meanwhile, an HF radio signal leaves the QAN transmitter at the azimuthal and elevation angles required to reach the enhancement, reflects off it, and then reaches the ALE receiver. In order to simplify the model, it is assumed that the refractive index is 1 (meaning the signal travels in a straight line at the speed of light) before and after reflection. In reality, the speed of an HF radio wave varies as it travels through the ionosphere. However, this effect only becomes significant near the reflection point for the signal. This model can be thought of as a limiting case for the actual dependence of TOF on deflection angle. The simplifying assumptions made about the enhancement crossing exactly halfway between QAN and ALE, moving exactly perpendicular to the path, are likely larger sources of error than assuming signals travel at the speed of light. Figure 1.12 illustrates the coordinate system, and the geometry of the one-hop propagation, with the horizontal deflection off the patch on the left (a), and the vertical reflection on the right (b).
Figure 1.12. Diagram showing an idealized 1-hop vertical reflection with lateral deflection off of an electron density enhancement. The left side (a) shows a top-down view, while the right side (b) shows a vertical view.

The expected TOF for the radio signal is simply twice the length of the vector from QAN to the enhancement \( r = \sqrt{r_{xy}^2 + r_z^2} \) divided by the speed of light \( c \). Referring to Figure 1.12, the horizontal component of this vector \( r_{xy} \) is \( \frac{d}{\cos(\theta)} \), where \( d \) is the distance from QAN to ALE, and \( \theta \) is the deflection from the GCH. The vertical component of the vector from QAN to the enhancement \( r_z \) is simply the reflection height \( h \). Therefore,

\[
r = \sqrt{h^2 + \frac{d^2}{4\cos^2\theta}},
\]

and the expected TOF is

\[
\text{TOF}(\theta) = \frac{2}{c} \sqrt{h^2 + \left(\frac{d}{2\cos\theta}\right)^2}.
\]

Overlaid in red and light blue on each panel in Figure 1.7 is the expected TOF as a function of deflection angle, assuming the one-hop deflection described in Equation 3. The red curves were calculated assuming a reflection height of 300 km (F-region) for deflections between \(-90^\circ\) and \(90^\circ\), while the blue curves were calculated assuming a reflection height of 100 km (E-region) for deflections between \(-45^\circ\) and \(45^\circ\). In each panel, the red TOF curves overlay the densest parts of the higher TOF population, suggesting that this part of the distribution is due to reflection off of F-region electron density enhancements such as polar cap patches or arcs. The spread around the red curves is likely due to variability in the reflection height over time. The light blue curves overlap the lower TOF population for deflections between \(-30^\circ\) to \(30^\circ\) deflection, but predicts a higher TOF than the lower population indicates for deflections larger than that. These E-region azimuthal deflections
could be due to low altitude arcs, but the separation between the two populations suggests an exclusively E-region phenomenon. Sporadic-E layers have been known to exhibit tilts of up to \(\sim 20°\) or more with respect to the horizon (e.g. From & Whitehead, 1978; Paul, 1990; Parkinson & Dyson, 1998). It is possible that some deflections in the lower TOF population are due to reflections off of tilted sporadic-E layers. There are also \(> 90°\) deflection signals in Figure 1.7, especially for the lower three frequencies, with lower TOFs than would be expected. These signals are possibly on-great circle signals that were deflected by nearby electron density enhancements drifting behind the receiver. They could also be signals that experienced local deflections near the receiver before being recorded.

This simple model can also be used to explain the shape of the Doppler shift - deflection distributions seen in Figure 1.8. The total Doppler shift experienced by an HF radio wave in the ionosphere is the accumulation of Doppler shifts experienced along the path as the wave travels through a non-stationary medium. In Figure 1.8, on-great circle signals for all frequencies experience little to no Doppler shift, suggesting that the majority of Doppler shifts are connected to azimuthal deflections. This is consistent with the simplifying assumption that the signal is in vacuum before and after reflection, and the total Doppler shift is entirely due to reflection off the density enhancement. The expected Doppler shift of a signal reflected off a surface moving parallel to the signal is

\[
\Delta f = \frac{2v_r f}{c},
\]

where \(v_r\) is the component of the velocity of the surface parallel to the wave vector, and \(f\) is the frequency of the wave. Since the electron density enhancement is moving in the \(x\) direction, the component of the enhancement velocity parallel to wave vector can be expressed as

\[
v_r = v \frac{r_x}{r},
\]

where \(v\) is the speed of the enhancement, \(r\) is the length of the vector from QAN to the enhancement, and \(r_x\) is the \(x\) component of that vector. \(r\) was found above in Equation 2, and \(r_x = \frac{d}{2}\tan(\theta)\) based on Figure 1.12. Pulling these together,

\[
v_r(\theta) = v \frac{d \tan \theta}{2\sqrt{h^2 + \frac{d^2}{4\cos^2 \theta}}},
\]

and the expected Doppler shift is

\[
\Delta f(\theta) = \frac{vf}{c} \frac{d \tan \theta}{\sqrt{h^2 + \frac{d^2}{4\cos^2 \theta}}},
\]
Overlaid on Figure 1.8 in red are curves showing Doppler shift versus deflection assuming a reflection height of 300 km, for enhancements moving at ±600 m/s relative to Qaanaaq and Alert. This speed is near the upper limit of possible speeds for an ionospheric density enhancement relative to the propagation path. It is the sum of the upper end of the distribution of polar cap patch speeds measured by Hosokawa et al. (2009) (~500 m/s), and the rotation speed of the Earth at the latitude of Qaanaaq (~100 m/s). In reality, these enhancements could be moving at a variety of speeds lower than 500 m/s, and at oblique angles relative to the propagation path, which in both cases would result in smaller Doppler shifts. Therefore, the red curves in Figure 1.8 can be considered upper limits on possible Doppler shifts for this radio link.

The Doppler shift curves bound the distributions of Doppler shifts at all frequencies well. An analysis of the data set showed that these Doppler shift limits bound at least 89% of signals with positive and negative deflections from the GCH between 2° and 90° for all frequencies, and at least 97% for the upper three frequencies. For the three lower frequencies, the distribution density does not reach the Doppler shift curves for deflection angles close to 90°. This is probably because there were not enough signals received at these deflection angles for an appreciable amount to have reflected off density enhancements moving perpendicular to the QAN–ALE line at sufficient speeds.

One final consideration that could influence the effect of off-great circle deflections on HF radio signal parameters is vertical motion of electron density enhancements. The drift of polar cap patches via ionospheric convection occurs due to an $E \times B$ drift involving the convection electric field and the Earth’s magnetic field. There is a non-zero vertical component to this drift wherever magnetic field lines are not oriented vertically, meaning patches tend to move upwards when drifting towards the pole and downwards after crossing the pole with speeds of tens of m/s (Hosokawa et al., 2019; Perry et al., 2013). If the reflection height changes with a constant speed,

$$ h(\theta) = h_0 + v_v \frac{d}{2v} \tan(\theta) $$

where $h_0$ is the reflection height at the crossing point, and $v_v$ is the vertical drift speed. Inserting this into Equation 3 shows that a vertical drift speed of even 100 m/s (with an $h_0$ of 300 km) does not result in a perceptible difference in the expected TOF. An additional vertical drift changes the expected Doppler shift equation, since it changes the component of the enhancement velocity relative to the wave vector. Accounting for vertical motion, this component is

$$ v_r = v \frac{r_x}{r} + v_v \frac{r_z}{r} = \frac{vr_x + v_v h(\theta)}{r}, $$

and the expected Doppler shift becomes
\[ \Delta f(\theta) = \frac{f v d \tan \theta + 2v_0 h(\theta)}{c \sqrt{h(\theta)^2 + \frac{d^2}{4 \cos^2 \theta}}} \]  

(10)

As with TOF, a vertical drift speed of even 100 m/s with \( h_0 = 300 \) km leads to an imperceptible difference in Doppler shift, at least for the simple patch crossing model described here.

1.6. Conclusions

This study evaluated nearly 2.5 years of 4.6 to 14.4 MHz radio propagation data from a high-latitude HF radio link to study off-great circle propagation in the polar cap region. A single day of received HF radio signals in which polar cap patch activity occurred was presented to establish how polar cap density enhancements can cause deflections from the expected angle of arrival. “Swings” in the azimuthal angle of arrival relative to the great circle heading (GCH); previously connected to polar cap patch crossings (Warrington et al., 1997), occurred during the parts of the day when the IMF \( B_z \) was negative. These swings were shown to be concurrent with time-of-flight (TOF) increases, Doppler shifts that transitioned from up to 30 Hz to as low as -25 Hz, and enhanced Doppler spreads of up to 65 Hz.

To determine the prevalence and magnitude of these deflections in general, a statistical analysis was performed. Examination of the distribution of signal deflections from the GCH for a largely uninterrupted year of transmissions showed that off-great circle propagation is commonly observed in the high-latitude ionosphere, and becomes increasingly prevalent with increasing frequency up to 11.1 MHz. This is because higher frequencies reach the F-region ionosphere more often, and can therefore be deflected by F-region density structures more often than lower frequencies. From April 2013 to April 2014, received 11.1 MHz signals arrived with deflections from the GCH of > 30° 65.6% of the time. The prevalence of these large deflections are highly dependent on time of day and year. An analysis of the weekly median magnitude of deflections over the year indicated that median deflections are largest in the winter for all frequencies, and tend to be close to zero in the summer. Further investigation of the prevalence of deflections versus UT time of day at different times of year showed that deflections for lower frequencies (4.6–8.0 MHz) are most common in the morning across the winter, while high frequencies (11.1–14.4 MHz) experience little to no deflections in the morning near the winter solstice. The high frequencies do experience significant deflections in the morning at the beginning and end of winter, however. The variation of deflections with respect to time of day and time of year for the high frequencies are consistent with a theory of patch generation involving dayside plasma being drawn into the polar cap by convection. The difference in UT distributions between high and low frequencies suggests a significant amount of lower frequency deflections (at least near the winter solstice) are due to electron density enhancements with peak densities or peak-to-background ratios too low to be considered polar cap patches.

An analysis of the full 2.5-year data set showed how the following HF radio signal properties change when the signals undergo large deflections from the GCH:

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• Signals deflected to off-great circle paths have generally larger TOFs, due to their necessarily longer propagation paths. The rate of increase in TOF with deflection is consistent with a simple model of reflection off of drifting localized enhancements at F-region altitudes crossing between QAN and ALE.

• The range of observed Doppler shifts is strongly dependent on deflection from the GCH, where larger deflections have a larger range of possible positive and negative Doppler shifts. This dependence is consistent with the same simple model of reflection off of drifting F-region enhancements, assuming the enhancements have drift speeds of up to 600 km/s relative to the propagation path.

• Off-great circle signals are associated with increased Doppler spreads, with spreads of up to ~35 Hz observed for 11.1 MHz signals.

• An analysis of the pointwise mutual information (PMI) between deflection from the GCH and signal-to-noise ratio (SNR) showed that signals with deflections of > ~20 deg are more likely to have SNRs of < ~30 dB. Conversely, signals with deflections of < ~20 deg are more likely to have SNRs of > ~30 dB.

Over-the-horizon radar (OTHR) operation is particularly sensitive to the deflection of HF radio waves to off-great circle paths and the accompanying TOF changes, since locating a target with OTHR requires knowledge of the propagation path to the target. These results suggest that any OTHR performing surveillance in the polar cap will frequently have to account for off-great circle deflections, especially in the winter. Left unaddressed, these deflections could lead to increased uncertainty in target location, while associated Doppler shifts and spreads could introduce uncertainty to velocity determination as well. As mentioned in the introduction, research is ongoing on how polar cap density enhancements affect OTHR coverage (Thayaparan et al., 2020, 2021). The results shown here could inform future research focused on mitigating the effects of off-great circle propagation on OTHR.

These results also represent a likely significant challenge for scientific OTHRs that are subject to polar HF radio propagation conditions—such as the polar component of the Super Dual Auroral Radar Network (SuperDARN). Off great-circle path deviations with SuperDARN radars have been reported in the past (e.g. Perry et al., 2016), but have not yet been specified or characterized with that system. Adding to the challenges is the fact that a reliable technique for identifying patches or instances of great-circle propagation has not yet been developed for the SuperDARN system. SuperDARN geolocation algorithms assume great-circle propagation (Chisham et al., 2008) which—as our results show—is often not the case in the polar-cap region. Studies are currently underway to determine the degree to which SuperDARN geolocation can be affected by off great-circle path deviations.
2. High-Latitude Off-Great Circle Propagation Associated with the Solar Terminator

This section contains an in-progress paper intended for submission to AGU Radio Science titled “High-Latitude Off-Great Circle Propagation Associated with the Solar Terminator” with the following authors: T. G. Cameron, R. A. D. Fiori, G. W. Perry, J. J. Ruck, and T. Thayaparan. The paper investigates the prevalence and strength of off-great circle deflections caused by the solar terminator using 3D numerical ray traces through model ionospheres.

2.1. Introduction

High frequency (HF) radio waves can propagate over very long distances by reflecting between the ionosphere and the ground. For this reason, HF radio propagation is used in many contexts, such as radio communications and over-the-horizon radar (OTHR). OTHR utilizes the long-distance propagation capabilities of HF radio waves to detect targets that can be thousands of kilometers away. Target detection and positioning relies on combining knowledge of the possible propagation paths taken by transmitted HF radio waves with the time-of-flight (TOF, travel time between transmitter and receiver) of received radio echoes. Therefore, determining the precise position of a target requires accurate, real-time models of the ionosphere, along with continual calculation of possible radio wave propagation paths (Thayaparan et al., 2018; Thayaparan, Warrington, et al., 2020).

Generally, HF radio waves travel along great-circle paths from a transmitter to a target location. However, horizontally aligned electron density gradients can alter radio wave trajectories, causing radio waves to travel via longer, off-great circle paths. Off-great circle propagation is detrimental to OTHR operation as it can cause substantial Doppler shifts, multipath spread, and other effects that can reduce received signal power or make it more difficult to receive a signal (Warrington et al., 2002; Warrington & Stocker, 2003).

Off-great circle propagation can also negatively affect OTHR operations indirectly. Coordinate registration, the process by which radar measurements in slant coordinates are transformed to geographical positions, depends on ray traces through a model of the ionosphere. Due to the requirement to operate in near-real time, full 3D numerical ray tracing is often computationally prohibitive and instead simpler 2D ray tracing techniques (e.g. Coleman, 1998, 2011) are employed. As these ray tracing methods strictly do not consider off-great circle propagation, deviations in the angle of arrival and time-of-flight associated with off-great circle propagation are likely to manifest significant target positioning errors. Frequency management, the process of determining which frequencies and elevations are expected to reach a position being surveilled (Thayaparan et al., 2019; Thayaparan, Marchioni, et al., 2020; Thayaparan et al., 2022), can also be impacted by off-great circle propagation. If propagation is assumed to be entirely on-great circle, or if a too limited azimuthal range of rays are traced, a frequency management system could miss valid propagation paths with a significant off-great circle component.
Electron density gradients associated with the solar terminator have been known to cause deflections of HF radio waves to off-great circle paths. Ross and Bramley (1947) reported the eastward deflection of radio waves up to 20° at times near sunrise, when the maximum usable frequency was near the wave frequency, for a ~400 km path, which they attributed to horizontal ionization gradients. Since the ionosphere is largely vertically stratified, these horizontal ionospheric gradients were frequently characterized as a wrinkling or tilting of the layers of the ionosphere. Ross and Bramley (1949) divided ionospheric tilts into two categories: systematic tilts caused by diurnal ionospheric variation, and random, localized tilts. Systematic tilts causing predictable deflections were seen around both sunrise and sunset, and were further investigated over the years using HF radio transmitters and receivers (e.g. Burtnyk et al., 1962; Morgan, 1974). Burtnyk et al. (1962) published statistics on the variance of ionospheric tilts measured for transmissions from Halifax and Washington, D.C. to Ottawa, while Morgan (1974) used weeks of HF bearing measurements to connect systematic ionospheric tilts to the solar zenith angle (SZA). Morgan (1974) studied both a north-south path and an east-west path. For the 1295 km north-south path, mean deflections between 0.7 and 1.2° were measured when \( \cos(SZA) \) was near zero, and the sun was near the horizon. They noted that east-west ionospheric tilts, and subsequent deflections, tended to be larger in the morning than the evening. The east-west path exhibited systematic deflections of 0.3−0.66°, for \( \cos(SZA) \approx 0.5 \).

The systematic deflection of radio waves due to large scale electron density gradients was studied by Tedd et al. (1985) with an ionospheric ray tracing model informed by ionospheric measurements from vertical sounders and experimental measurements. Tedd et al. (1985) reproduced off-great circle deflections in north-south radio wave propagation paths due to east-west gradients in the ionospheric electron density. However, the model could not reproduce deflections observed in east-west propagation paths. They attributed this to their ionospheric model not accurately reproducing the associated north-south electron density gradients, which were attributed to plasma transport processes.

In recent years, research has shifted to investigate how localized high-latitude ionospheric density structures such as polar cap patches and high-latitude arcs can cause off-great circle propagation (e.g. Warrington et al., 1997; Zaalov et al., 2003; Warrington et al., 2012; Siddle et al., 2013). Studies have utilized a combination of HF radio transmitter/receive networks, ray tracers, and ionospheric models. Off-great circle propagation caused by these density structures are not as predictable as the systematic ionospheric tilts described above, but have been shown to cause deflections from the great circle path of up to 100° (Warrington et al., 1997). Off-great circle propagation due to interaction with the mid-latitude ionospheric trough has also been studied similarly (e.g. Stocker et al., 2003; Warrington & Stocker, 2003; Stocker et al., 2009), as well as off-great circle propagation associated with aurora (e.g. Bates et al., 1966; Hunsucker & Bates, 1969; Rogers et al., 2003).

Thayaparan et al. (2021) studied off-great circle propagation caused by localized ionospheric density structures in the context of OTHR. They performed ray tracing simulations of HF radio wave propagation through a model ionosphere with added model polar cap patches. These model patches resulted in deflections from the great circle heading of up to 35°. They showed how the presence of these patches affected both the range of available frequencies for propagation to some target and signal parameters such
as the TOF. Ruck and Themens (2021) presented a case study for a hypothetical OTHR using ray traces through model ionospheres with modelled auroral ionization. In this study, coverage area was observed outside the nominal field of view of the radar and attributed to horizontal deflections of rays due to aurora.

While ionospheric disturbances can cause large deflections of radio waves to off-great circle paths during active conditions, large scale east-west gradients associated with diurnal ionospheric variation near the solar terminator at dawn and dusk could cause appreciable off-great circle propagation in north-south aligned paths during both active and quiet conditions. While studies such as Tedd et al. (1985) investigated this effect with a limited number of ray traces through basic ionospheric models, massive increases in computational power have since occurred, significantly reducing the amount of time required to complete a ray trace, enabling a larger study. Additionally, much more accurate, 3D ionospheric models built from millions of measurements of ionospheric electron density now exist. These models are able to reproduce the large scale structure of the ionosphere to a degree that was impossible in the 20th century. These two factors allow for a much more comprehensive study of diurnal off-great circle propagation.

In this paper, 3D numerical ray tracing simulations though model ionospheres are used to perform a comprehensive study of off-great circle propagation caused by horizontal ionospheric gradients associated with the solar terminator. The occurrence and magnitude of off-great circle deflections are explored across all four seasons, at all times of day, for a variety of different propagation directions at high latitudes. Section 2.2 describes the ray tracer and model ionosphere used in this study. Section 2.3.1 shows results concerning off-great circle deflections caused by the solar terminator for three hypothetical northward paths, while Section 2.3.2 presents results concerning the same kind of off-great circle deflections for arbitrarily oriented paths. Section 2.4 discusses the impacts these deflections could have on HF radio technology used at high latitudes, such as OTHR.

2.2. Methods

Radio wave propagation paths are predicted using three-dimensional (3D) ray tracing techniques, in which radio wave trajectories are approximated by a series of one-dimensional rays. Ray trajectories are determined using ionospheric models and numerical integration techniques. In this study, ray traces were performed using a modified version of the Jones and Stephenson (1975) ray tracer. This ray tracer works by calculating the index of refraction throughout a model ionosphere with the Appleton-Hartree equations, and then numerically integrating the Hamiltonian ray path equations (Haselgrove, 1963) for a series of rays with differing initial transmission directions. Modifications to Jones and Stephenson ray tracer, described in Zaalov et al. (2005), allow for the radio wave trajectories to be traced through an arbitrarily defined model ionosphere supplied as a 3D grid of electron density values. For the ray traces described below, all propagation was assumed to be O-mode, the Earth was assumed to be a perfect spherical reflector, a simple built-in dipole model was used to determine magnetic field values, and collisions were ignored.

In order to accurately reflect the large scale structuring of the high-latitude ionosphere, the Empirical Canadian High Arctic Ionospheric Model (E-CHAIM) (Themens et al., 2017,
2019) version 3.3.0 was used to generate electron density values for the ray tracer. E-CHAIM is an empirical model of the high-latitude (> 50° magnetic latitude) ionosphere, in which electron density is determined with a series of spherical cap harmonic expansions of ionospheric sub-layers. Determined from millions of radio occultation and ionosonde measurements, E-CHAIM generates model ionospheres tailored to specific dates and times, incorporating diurnal, seasonal, and solar cycle variability. ECHAIM is even able to reproduce large-scale ionospheric variability tied to geomagnetic activity, though the focus of this paper is the undisturbed ionosphere.

E-CHAIM also includes several optional sub-models that extend its ability to represent high-latitude ionospheric structuring and variation. The D-region sub-model adds additional electron density representing the D-region, the NmF2 storm model modifies the F2 region to reflect structuring associated with auroral activity (even during quiet times), and the precipitation sub-model adds additional E and F-region ionization connected to auroral activity during active times. Since D-region electron density is too low to have any appreciable effect on HF radio wave trajectories, and since all times studied were too quiet for the precipitation model to have any effect, only the NmF2 storm sub-model was used in this study.

2.3. Analysis and Results

2.3.1. North Directed Paths

Ray traces simulating O-mode HF radio propagation were performed through models of the high-latitude northern ionosphere generated with E-CHAIM for 20 March 2020, 21 June 2020, 22 September 2020, and 21 December 2020, representing ionospheric conditions indicative of spring, summer, fall, and winter respectively. For each date, ray trace runs were performed through ionospheres generated for every hour from 00:00 to 00:05 UTC (Coordinated Universal Time) the following day, allowing for the full day in both UTC and EST (Eastern Standard Time) to be represented. Rays were traced from Ottawa with initial azimuths ranging from −90° to 90° in 0.5° increments, at initial elevations from 3° to 89° in 0.2° increments, at frequencies ranging from 3 to 18 MHz, in 0.5 MHz increments. In total, approximately 1.16 billion rays were traced.

Off-great circle propagation was studied for a north-south path for three target locations. For the first part of this study, three target locations were selected, all north of Ottawa. Targets 1, 2, and 3 were located 1000 km, 2000 km, and 3000 km north of Ottawa along the great circle at coordinates of (54.4° N, 75.7° W), (63.4° N, 75.7° W), and (72.4° N, 75.7° W), respectively, see Figure 2.1.
Figure 2.1. Maps showing the great circle paths for each of the three target locations used in this study. (a) Target 1 is located at (54.4° N, 75.7° W), (b) Target 2 is located at (63.4° N, 75.7° W), and (c) Target 3 is located at (72.4° N, 75.7° W). Black circles indicate a radius of 100 km around the target within which rays were considered to have reached the target. Black lines indicate the great circle path to the target, and red lines indicate the east-most and west-most boundaries of the great circle paths within the 100 km target radius. Maps are plotted with the Albers equal area conic projection and geographic coordinate system.

Rays landing within 100 km of the target (indicated by black circles in Figure 2.1) were considered to have reached the target, and were considered for analysis. For each selected ray, the difference between both the transmitted and received azimuth and the great circle heading (GCH) was calculated. The GCH is the initial azimuth from the transmitter, or final azimuth from the landing point, that a ray travelling entirely along the great circle path would have. Crucially, the GCH was calculated separately for each ray, based on the final impact point of the ray (which is within 100 km of the target location). The GCH was subtracted from the transmitted or received azimuth for each ray, yielding lists of azimuthal differences from the GCH. These differences are referred to as “azimuthal shifts” going forward, and were generated for each target and time pair. Azimuthal shifts are positive clockwise. This means that for north-directed propagation, transmitted azimuthal shift is positive for signals transmitted east of north and negative for signals transmitted west of north, while received azimuthal shift is positive for signals received west of south and negative for signals received east of south.

Signal power contributions were calculated for each ray path based on the theoretical transmitter power, transmitter and receiver antenna gain, D-region absorption, and the fractional solid angle apportioned to each ray based on the density of rays emitted by the transmitter. These signal power contributions were binned according to frequency and azimuthal shift and summed to arrive at received signal power as a function of frequency and azimuthal shift for each target and time. A transmitter power of 500 W was used for the signal power calculation, and both the transmitter and receiver antennas were assumed to be simple vertical monopoles. D-region absorption was calculated separately for each ray path using a simple solar absorption model (Lucas & Haydon, 1966).

Figure 2.2 shows received signal power received at Target 1 as a function of frequency and transmitted azimuthal shift (Figure 2.2a), or received azimuthal shift (Figure 2.2b) for rays traced through an E-CHAIM ionosphere for 21 December 2020 at 17:00 UTC. Three distinct bands of signal power are clearly seen, corresponding to different (vertical)
propagation paths from the transmitter to the target. In this case, the bands correspond to differing numbers of hops between the transmitter and target. For transmitted azimuthal shift (Figure 2.2b), the upper band (1 hop) shows close to zero azimuthal shift, the middle band (2 hop) exhibits positive (eastward) azimuthal shifts of up to $\sim 2^\circ$, and the lower (3 hop) band exhibits positive (eastward) azimuthal shifts of up to $\sim 3^\circ$. The magnitude of the shift varies depending on frequency, with higher shifts observed near the peak frequency for each band.

Figure 2.2. Received signal power versus frequency and (a) transmitted or (b) received azimuthal shift for rays transmitted directly north from Ottawa through an E-CHAIM ionosphere generated for 21 December 2020 17:00 UTC received at Target 1 (54.4° N, 75.7° W). Azimuthal shift refers to the difference between the transmitted or received azimuth and the great circle azimuthal direction to the target or transmitter, respectively. Bands of signal power are labelled according to how many hops corresponding rays took before reaching Target 1.

Figure 2.2b is almost a mirror image of Figure 2.2a, consistent with expectations given the geometry. If a ray transmitted east of the great circle path (a positive shift from the transmitter’s perspective) experiences an electron density gradient bending its trajectory west, it would reach the target at an azimuth slightly east of the great circle path. From the perspective of the receiver, this azimuthal shift would be negative. There are small differences between panels a and b in the shape and intensity of the received bands of signal power. These differences are likely due to ionospheric structuring present in the E-CHAIM generated ionosphere breaking the symmetry of the propagation path arcs.

Figure 2.3 shows received signal power on 20 June 2020 as a function of frequency and azimuthal shift at four times of day (00:00, 04:00, 12:00, and 20:00 EST from the top down), reflecting local midnight, the hour closest to sunrise, noon, and the hour closest to sunset, for rays reaching each of the three targets (Targets 1, 2, and 3 from left to right). All local sunrise and sunset times were calculated for the transmitter location in Ottawa.
Figure 2.3. Received signal power versus frequency and transmitted azimuthal shift from the GCH for rays transmitted from Ottawa. From the top down, rows of panels show received signal power for rays transmitted through an E-CHAIM ionosphere generated for 20 June 2021 at (top) 00:00, (upper middle) 04:00, (lower middle) 12:00, and (bottom) 20:00 EST. From left to right, columns of panels show received signal power for rays reaching (left) Target 1 (54.4° N, 75.7° W), (middle) Target 2 (63.4° N, 75.7° W), and (right) Target 3 (72.4° N, 75.7° W).

At 00:00 EST (local midnight, top panels), signal power is received for frequencies up to 4, 6.5, and 8.5 MHz for targets 1, 2, and 3 respectively. For all three targets, the received signal is almost entirely on-great circle, as expected for midnight. At 04:00 EST (local sunrise, panels second from top), signal power is received for all three targets at frequencies up to 5, 8.5, and 11 MHz respectively. The increased range of received frequencies is due to the higher electron density in the morning compared to midnight. The received signal power for all three targets exhibit eastward shifts of up to 9°, 5.25°, and 2° respectively. At 12:00 EST (local noon, panels third from the top), signal power is received at the three targets for frequencies up to 13, 17, and 16.5 MHz respectively, with azimuthal shifts generally < 3° for all targets. Increased D-region absorption at noon has resulted in the signal power near 3 MHz being less than the -130 dBm lower limit of the figure. Finally, at 20:00 EST (local evening, bottom panels) signal power is received at the
three targets at frequencies up to 9.5, 14, and 17 MHz respectively. Similar to local morning, there are large westward shifts from the GCH of up to 12.75°, 7.5°, and 4°.

This figure exhibits a pattern in which HF radio waves experience large eastward shifts in the morning, and large westward shifts in the evening, consistent with deflections caused by ionospheric gradients associated with the solar terminator. The largest shifts tend to occur for frequencies near the maximum usable frequency (MUF) for a given band of signal power or propagation mode. This makes sense, since frequencies near the MUF spend the most time interacting with the ionosphere. The lowest frequencies also exhibit larger shifts than the middle of the frequency range, seen most clearly at 20:00 EST, likely because the lowest frequencies are the most susceptible to refraction. Additionally, bands of signal power corresponding to more hops exhibit larger azimuthal shifts, likely because more hops mean more interactions with the ionosphere. Comparing propagation to the three targets at different distances from Ottawa, increasing distance tends to lead to a smaller range of azimuthal shifts.

Figure 2.4 shows received signal power on 21 December 2020 for the same three targets, at four times in a similar grid pattern to Figure 2.3. The four times plotted from the top down are 00:00, 08:00, 12:00, and 16:00 EST, reflecting local midnight, the hour closest to sunrise, noon, and the hour closest to sunset. These panels are very similar to those presented in Figure 2.4. At 00:00 EST (local midnight, top panels), little to no azimuthal shift is seen for propagation to all three targets. Large eastward azimuthal shifts of up to 27.25°, 13°, and 12° are seen for propagation to the three targets respectively at 08:00 EST (local sunrise, panels second from the top). Smaller azimuthal shifts of < 4° are seen for all three targets at 12:00 EST (local noon, panels third from the top). Substantial westward azimuthal shifts of up to 12.75°, 8°, and 5.25° are seen for propagation to targets 1, 2, and 3, respectively, at 16:00 EST (local sunset, bottom panels). Propagation on 21 December 2020 exhibits similar patterns in terms of azimuthal shift to 20 June 2020. Substantial shifts are seen at sunrise and sunset, the largest shifts are seen near the MUF for a given propagation mode and time, and the range of shifts decreases with distance. Signal power as a function of azimuthal shift and frequency was also examined for 20 March 2020 and 22 September 2020. Broadly, variation in azimuthal shift was found to be similar to the two dates shown above. Figures showing signal power versus frequency and azimuthal shift at key times for 20 March 2020 and 22 September 2020 can be seen in Figures 2.A1 and 2.A2 respectively.
Figure 2.4. Received signal power versus frequency and transmitted azimuthal shift from the GCH for rays transmitted from Ottawa. Rows of panels show received signal power for rays transmitted through an E-CHAIM ionosphere generated for 21 December 2020 at (top) 00:00, (upper middle) 08:00, (lower middle) 12:00, and (bottom) 16:00 EST. From left to right, columns of panels show received signal power for rays reaching (left) Target 1 (54.4° N, 75.7° W), (middle) Target 2 (63.4° N, 75.7° W), and (right) Target 3 (72.4° N, 75.7° W).

Figures 2.3 and 2.4 show that azimuthal shift from the GCH varies substantially with frequency, and that there can even be a large observed range of azimuthal shifts for a single frequency. For propagation to each target at each time, the “characteristic shift” was defined as the azimuthal shift corresponding the largest received signal power at the frequency resulting in the largest total received signal power. Figure 2.5 shows characteristic shift from the GCH as a function of time for transmitted azimuth (left) and received azimuth (right), for the three targets (top to bottom), for four different dates in 2020 (20 March, 20 June, 22 September, and 21 December, each indicated by color and line style). Local sunrise and sunset times for each date are indicated by vertical dashed lines, with date indicated by the same color and line style as the characteristic shift from the GCH.
Figure 2.5. Characteristic azimuthal shift from the GCH as a function of time for rays received at (top) Target 1 (54.4° N, 75.7° W), (middle) Target 2 (63.4° N, 75.7° W), and (bottom) Target 3 (72.4° N, 75.7° W) for all four dates simulated (20 March, 20 June, 22 September, and 21 December 2020, each indicated by color and line style). The left column shows the transmitted azimuthal shift from the GCH, and the right shows the received azimuthal shift from the GCH. Different colors and line styles distinguish the day the E-CHAIM ionospheres were generated. Vertical lines show local sunrise and sunset times for each date, distinguished by color and line style.

Propagation to all three targets shows clear, smooth variation across the day in both the transmitted and received azimuthal shifts, for all four days simulated. The characteristic azimuthal shift (transmitted) from the GCH reaches up to 2° for Target 1, 3° for Target 2, and 4.5° for Target 3. The largest transmitted shifts are positive (eastward) in the morning, and negative (westward) in the evening, and the largest received shifts are negative in the morning and positive in the evening. While previous plots showed that the range of shifts decreased with increasing distance, here the farther targets tend to have larger characteristic shifts associated with them. This is due to changes in which propagation mode carries the most signal power with increasing distance. For Target 1 (1000 km north of Ottawa), 1 hop propagation carries the most signal power, while for Targets 2 and 3 (2000 and 3000 km north of Ottawa, respectively), 2 and 3 hop propagation carries more signal power. So while the range of shifts for a given number of hops decreases with distance, the transition to multiple hop propagation means that the majority of signal power arrives with larger azimuthal shifts with increasing distance.

As expected, the largest shifts generally line up with local sunrise and sunset, though for some dates the largest shifts are more than an hour removed from sunrise/sunset. For example, the peak transmitted shift to Target 3 on 21 December 2020 happens at 09:00 EST, while the sunset time on this date was at 07:39 EST. These discrepancies could be due to E-CHAIM reproducing spatial variations in electron density not related to the solar terminator, even during quiet conditions. Additionally, at high latitudes, the solar terminator is not aligned north/south in the winter and summer due to the Earth’s tilt. Local sunrise and sunset times are therefore not always constant along north directed propagation.
paths, and the resulting ionospheric electron density gradients are not simply east/west, leading to a more complicated relationship between azimuthal shift and time of day and propagation path.

However, the high latitude ionosphere is more complicated structurally due to the tilt of the Earth, and this analysis has been restricted to northward propagation paths so far. In the next part of this study, azimuthal shift due to the solar terminator is studied for a wide variety of propagation paths pointed in different directions.

### 2.3.2. Mapping Azimuthal Shift for Varied Propagation Paths

To examine how different propagation paths are affected by the solar terminator, the characteristic azimuthal shift was calculated for a variety of target locations to create maps of expected azimuthal shift from Ottawa. Target locations were chosen ranging from $-65^\circ$ to $65^\circ$ in azimuth from Ottawa, at distances of 100 to 4000 km, each separated by 100 km. To increase the resolution of the resulting map, the target circle radius was reduced from 100 km to 50 km. Comparison of 50 km radius target circles to 100 km radius target circles showed little to no difference in resulting azimuthal shift. Figure 2.6 shows the location and radius of every target circle considered.

![Figure 2.6](image)

**Figure 2.6.** Map showing the location and radius of target circles used to make maps of azimuthal shift.

Signal power versus frequency and azimuth was calculated for each target circle in Figure 2.6 for every date and time as described in the previous section. Then, the characteristic shift was calculated for each target each by selecting the frequency for which the greatest signal power was received, and then selecting the transmitted azimuthal shift corresponding to the greatest received signal power at that frequency. Figure 2.7 shows maps of the ionospheric critical frequency output from E-CHAIM (left), and the expected characteristic transmitted azimuthal shift for propagation from Ottawa (right) for four times on 20 June 2020. From the top down, mapped times are 05:00 UT (local midnight), 09:00 UT (hour closest to local sunrise), 17:00 UT (local noon), and 01:00 UT the next day (hour closest to local sunset). Targets with magnetic latitudes < $50^\circ$ were removed from the maps.
Figure 2.7. Maps of modeled ionospheric critical frequency from E-CHAIM (left) and expected characteristic transmitted azimuthal shift for propagation from Ottawa (right) for four times on 20 June 2020. From the top down, maps show critical frequency and characteristic azimuthal shift for 05:00 UT (local midnight), 09:00 UT (hour closest to local sunrise), 17:00 UT (local noon), and 01:00 UT the next day (hour closest to local sunset). Thick black lines on each map indicate the position and orientation of the solar terminator at the corresponding time.
At 05:00 UT (top row), the solar terminator is far north of Ottawa and oriented east/west, since the North Pole is in constant sunlight. Ionospheric critical frequency (left) is slightly lower south of the terminator and northwest of Ottawa at this time. Azimuthal shift (right) is approximately zero across the whole map, other than small shifts for very eastward and westward paths. At 09:00 UT (second row from top), the solar terminator is oriented northwest, passing close to Ottawa. As a result, critical frequency (left) west of the terminator is markedly lower than the east of the terminator. This distribution of electron density has resulted in large, > 5° azimuthal shifts for longer propagation paths oriented west of north (right). The largest shifts are seen for paths that are roughly parallel to or westward of the solar terminator.

At 13:00 UT (third row from top), critical frequency (left) is approximately constant across the map, and the accompanying map of azimuthal shift (right) is close to zero everywhere. At 17:00 UT (bottom row), the solar terminator is oriented northeast, passing near Ottawa. Ionospheric critical frequency (left) is higher west of the solar terminator, though there is a region of relatively lower daytime critical frequency between 55° and 65° latitude west of the solar terminator. The resulting map of azimuthal shift (right) shows shifts of up to approximately 3° for longer, eastward propagation paths, especially east of the solar terminator. There are also smaller shifts for far west paths, possibly due to the previously mentioned localized region of relatively low daytime critical frequency.

Overall, there is a clear pattern seen in Figure 2.7 in which the largest shifts occur for propagation paths oriented parallel to or west of the solar terminator in the morning, and for propagation paths oriented parallel to or east of the terminator in the evening. Since the solar terminator is oriented at an angle with respect to north at high latitudes in the summer, this means that generally, westward propagation paths experience the largest deflections in the morning, and eastward propagation paths experience the largest deflections in the evening.

Figure 2.8 shows maps of ionospheric critical frequency (left) and expected characteristic transmitted azimuthal shift for propagation from Ottawa (right) for four times on 21 December 2020. From the top down, mapped times are 05:00 UT (local midnight), 13:00 UT (hour closest to local sunrise), 17:00 UT (local noon), and 21:00 UT (hour closest to local sunset). Broadly, deflections follow a similar pattern to Figure 2.7, except the orientation of the solar terminator in morning and evening, and the resulting propagation directions corresponding to the largest shifts are reversed. This means that propagation paths oriented northeast lead to the largest azimuthal shifts near sunrise, and northwest propagation paths lead to the largest azimuthal shifts near sunset. At midnight and noon, little to no shifts are seen. Ionospheric critical frequency (left column) at all four times is more varied than in the summer, reaching higher maximums and lower minimums. This means horizontal ionospheric gradients are generally larger, and the resulting azimuthal shifts in the morning and evening are also larger and more widespread than in the summer.
Figure 2.8. Maps of modeled ionospheric critical frequency from E-CHAIM (left) and expected characteristic transmitted azimuthal shift for propagation from Ottawa (right) for four times on 21 December 2020. From the top down, maps show critical frequency and characteristic azimuthal shift for 05:00 UT (local midnight), 13:00 UT (hour closest to local sunrise), 17:00 UT (local noon), and 21:00 UT (hour closest to local sunset). Thick black lines on each map indicate the position and orientation of the solar terminator at the corresponding time.
Maps of characteristic transmitted azimuthal shift and critical frequency were also calculated and produced for 20 March 2020 (Figure 2.A3), and 22 September 2020 (Figure 2.A4) in the same format as Figures 2.7 and 2.8. On these dates, the solar terminator is oriented entirely northward at sunrise and sunset. At sunset on both dates, northward paths exhibit small negative shifts of < 3°. However, northwest propagation paths exhibit large, positive shifts of > 5° at sunrise on both dates.

To quantify how azimuthal shift can be expected to vary with direction of propagation, characteristic azimuthal shifts were binned according to the great circle azimuth to the corresponding target, and the average shift was calculated in each bin. Only targets > 1000 km away were considered, since most of the shift variations with angle in the maps were seen for larger distances. Figure 2.9 shows the average transmitted (left column) and received (right column) characteristic shift versus azimuthal angle of propagation to the target for 20 March, 20 June, 22 September, and 21 December 2020 at 4 times of day. From the top down, panels show shift for local midnight (top), the hour closest to sunrise (second from top), local noon (third from top), and the hour closest to sunset (bottom).

![Figure 2.9](image)

**Figure 2.9.** Average magnitude of characteristic (left) transmitted and (right) received azimuthal shift versus azimuthal angle of propagation on 20 March, 20 June, 22 September, and 21 December 2020 (each indicated by color and line style) at four times of day. From the top down, panels show shift versus angle of propagation for local midnight, the hour closest to sunrise, local noon, and the hour closest to sunset.

At both midnight (top) and noon (third from top), the average magnitude of transmitted azimuthal shift is almost entirely ≤ 1° regardless of angle of propagation or date. The
accompanying received azimuthal shift is also low at noon for all angles and dates, but reaches up to ±2.5° for angles 45° or < −45°. At the hour closest to sunrise (second from top), the average transmitted shift is almost entirely positive, and increases with decreasing propagation angle, reaching between 3° and 5° for 20 March, 20 June, and 22 September 2020. The average transmitted shift at sunrise on 20 December 2020 is also entirely positive, and increases with increasing propagation angle. It reaches a maximum of ~4° for a ~20° angle of propagation, though negative propagation angles still experience average shifts of ~2°. Received azimuthal shift at the hour closest to sunrise approximately mirrors transmitted shift with respect to the x-axis.

At the hour closest to sunset (bottom), the average transmitted shift is almost entirely negative for all angles and dates, while the average received shift is almost entirely positive for all angles and dates. The average transmitted and received shift is close to zero on 20 March and 22 September 2020, with the magnitude only reaching as high as 1° for negative (westward) propagation angles. Average transmitted shift at the hour closest to sunset on 20 June 2020 decreases from ~1° to ~2.5° with increasing propagation angle, while average transmitted shift for 21 December 2020 decreases with decreasing propagation angle, peaking at 3° for a ~20° angle of propagation. Overall, the average magnitude of transmitted and received azimuthal shifts is smaller on the hour closest to sunset when compared to sunrise.

2.4. Discussion

Ray tracing simulations of HF radio propagation at high latitudes over Canada show that north-directed HF radio waves can be deflected by horizontal ionospheric gradients by up to 20° near sunrise and sunset, and even exceeding 20° in some cases. These deflections were shown to be largest for frequencies near the maximum usable frequency for a given propagation mode, and for multiple hop propagation modes. These results are consistent with the observations by Ross and Bramley (1947), who recorded deviations of up to 20° in the received bearing of radio transmissions when the maximum usable frequency (MUF) was near the transmission frequency, albeit for a shorter path. Larger deviations being associated with radio wave frequencies near the MUF was also noted by Tedd et al. (1985). It is well known that HF radio wave trajectories show increased sensitivity to electron density changes near the MUF (Warrington et al., 1997; Titheridge, 1958), so it is not surprising that the largest azimuthal deviations are seen near the MUF.

In practice, HF radio operators tend to use an operating frequency that results in the highest received signal power. The azimuthal deflection experienced by the majority of signal power at the best performing frequency was tracked over the course of the day for four dates spaced equally across the year. This characteristic shift was shown to vary across the day, peaking at around ~5° in one direction near local sunrise, and in the opposite direction near local sunset. While the range of azimuthal shifts experienced by radio waves was found to decrease with increasing propagation distance, the characteristic shift was found to increase with increasing distance. This is because multiple hop propagation modes carry more of the signal power for longer distances, and these modes experience larger deflections than single hop modes since they interact with the ionosphere multiple times. It should be noted that the azimuthal shifts modelled here are
the result of a smoothed ionospheric model, and that the real propagation environment is substantially more complex.

Since ray tracing simulations were performed for a wide range of initial azimuths, it was possible to explore azimuthal deflections experienced by paths oriented away from north. Maps showing the characteristic azimuthal shift experienced by HF radio waves for a variety of locations across Canada, for different times of day and year were generated, and these were used to quantify the average characteristic azimuthal shift versus propagation direction. It was found that propagation paths oriented tens of degrees away from north can experience azimuthal shifts associated with the solar terminator equal to or even greater than shifts experienced on north-directed paths in the morning and evening.

For the hour closest to sunrise, the average characteristic shift was found to be largest for northwest paths in the summer, and largest for northeast paths in the winter. This behavior was reversed for the hour closest to sunset, where northeast paths experienced the largest shifts in the summer, and northwest paths experienced the largest shifts in the winter. This is consistent with the orientation of the solar terminator at these times of day and year, such that the largest shifts are experienced by paths approximately parallel with the solar terminator.

Large (> 3°) average characteristic azimuthal shifts were observed for northwest propagation paths in the hour closest to sunrise on 20 March, 20 June, and 22 September 2020. Average northwest shifts > 1.5° were even seen at this time on 21 December. These shifts do not appear to be connected to the solar terminator, except for those on 20 June 2020. Referring to the maps of critical frequency at the hour closest to sunrise on all four dates (left, second row from the top in Figures 2.7, 2.8, 2.A3, and 2.A4), these shifts appear to be caused by a band of increased critical frequency at ∼65°. This band is the result of quiet-time soft auroral electron precipitation, which E-CHAIM includes as part of its “storm” model option. Off-great circle deviations caused by auroral ionization were noted by Ruck and Themens (2021) in a case study using ray tracing simulations through an E-CHAIM model ionosphere as well. While outside the scope of this study, future work could address this effect for geomagnetically active times.

The results shown in this study could have implications for the operation of OTHR. While an ordinary radar is able to determine the position of a target from the TOF and assuming a straight-line path to the target, the same determination with an OTHR requires information about the propagation paths used to reach the target and is determined during the coordinate registration process. This study has shown that at certain times of day, HF radio propagation paths can have an appreciable off-great circle component. If these off-great circle components are not accounted for, such as in coordinate registration systems utilizing 2D numerical ray-tracing, an azimuthal deflection of even a few degrees could lead to large errors in locating a target.

One option for avoiding the largest azimuthal shifts, while it would mean less received signal power, could be to use an operational frequency markedly lower than the MUF. However, support for such frequencies may not always be available. Alternatively, checking empirical models of the ionosphere such as E-CHAIM for substantial horizontal
ionospheric gradients could give OTHR operators information about when large azimuthal deflections can be expected. It is expected that for a coordinate registration system utilizing 3D ray tracing and a suitable model ionosphere such as E-CHAIM, the effects of off-great circle propagation can effectively be mitigated as we demonstrate here that such azimuthal shifts can be modelled for large scale gradients. Utilizing 3D ray tracing will necessarily require substantially increased computation time, however.

Frequency management systems supporting OTHR are also expected to experience impacts from off-great circle deflections. These systems use numerical ray tracing and accurate ionospheric models to determine which frequencies and elevation angles are suitable for surveilling some region at a given time (Thayaparan, Warrington, et al., 2020). During operational conditions, these ray trace runs are often time-limited, meaning as few rays as possible are traced, and often only in the great circle direction to the target. These results indicate that operational ray traces should include a range of initial azimuths around the GCH to ensure that off-great circle paths to a target are accounted for. This range is obviously limited by time constraints, but the average azimuthal shifts seen in Figure 2.5 indicate that if possible, rays should be traced with azimuths up to 5° from the GCH to ensure the propagation paths carrying the majority of the signal power to a target are accounted for.

While the significance of off-great circle propagation has been demonstrated here for a one-way path to arbitrary targets, azimuthal shifts could be more complicated for OTHR in practice when bistatic or multistatic receiver arrangements are considered. This is because providing that the transmitter and receiver are separated by a large distance, rays received at the receiver will have passed through substantially different regions of the ionosphere for the transmitter to target and target to receiver paths. This implies that the azimuthal shifts experienced at the receiver will be the result of deflections from the ionospheric gradients encountered on both legs.

It should also be noted that the azimuthal deflections studied here are much smaller than deflections caused by localized ionospheric structures such as polar cap patches. Deflections caused by polar cap patches are often > 30°, and are often accompanied by large Doppler shifts and reduced signal power (e.g. Warrington et al., 1997). These large effects likely make deflections caused by ionospheric structures much easier to detect and identify when compared to deflections caused by the solar terminator, which could have less noticeable, but still detrimental effects on HF radio technologies. Luckily, deflections caused by the solar terminator tend to be isolated to the morning and evening, and are more predictable in terms of direction and magnitude.

The effect of off-great circle propagation due to the day/night terminator on the accuracy of HF systems relied upon in solar-terrestrial physics, such as the Super Dual Auroral Radar Network (SuperDARN; Chisham et al., 2007) have not yet been thoroughly investigated. SuperDARN detects coherent backscatter caused by field-aligned ionospheric plasma density irregularities which—at F-region altitudes—drift at the local plasma convection velocity (Ruohoniemi et al., 1987). Therefore, line-of-sight Doppler velocity measurements from multiple SuperDARN radars can be combined to determine a convection velocity over a large geographic region.
One important assumption in SuperDARN’s methodology is that its transmissions are expected to follow a round-trip great-circle path to and from the scattering volume. Recently, Perry et al. (2022) demonstrated that this assumption is appropriate some of the time; however, they did not investigate how robust this assumption is with respect to the day/night terminator. Given that the off-great circle path deviations reported here often exceed the nominal bearing resolution (referred to as a “beam width” in the SuperDARN community) of the SuperDARN system, which is approximately 3.24°, it is possible that the day/night terminator may have a small, albeit non-negligible, effect on SuperDARN line-of-sight velocity measurements. It is left to future work to quantify the scale of this effect and analyze SuperDARN data to determine whether the effect is discernible.

2.5. Summary and Conclusions

In this study, an investigation of off-great circle propagation caused by large scale electron density gradients associated with the solar terminator was performed. A series of ray traces were performed through model ionospheres generated with E-CHAIM for each hour of the day for four characteristic days of the year (20 March 2020, 20 June 2020, 22 Sept 2020, and 21 December 2020). These ray traces showed that during the morning and evening, large scale east-west ionospheric gradients associated with diurnal ionospheric variation can cause parts of HF radio signals to be deflected by up to and sometimes exceeding 20° from the GCH. Deflections of up to 5° were experienced by the majority of signal power at these times, at the best performing frequencies. Larger deflections were seen for frequencies near the MUF, and for multi-hop propagation paths. Since multiple hop modes become dominant for longer propagation paths, azimuthal shift tends to be larger for longer propagation paths.

An investigation of propagation paths oriented at a range of directions relative to north showed that even highly inclined propagation paths can experience large azimuthal deflections caused by the solar terminator. The largest factor influencing these deflections was the orientation of the solar terminator relative to the propagation direction. Since the solar terminator is inclined with respect to north in the summer and winter at high latitudes, inclined propagation paths at these times of year will experience larger azimuthal shifts than north directed paths in the morning and evening.

The azimuthal shifts reported in this study could be a previously unknown source of error for OTHRs, which rely on a strictly great circle assumption of propagation. Even a few degrees shift in the angle of arrival could mean a large error in the derived position of a target. Strategies for minimizing this error could involve utilizing a lower operating frequency to avoid the largest azimuthal shifts, or utilizing empirical ionospheric models to determine expected azimuthal shifts ahead of time.

Large scale gradients associated with the auroral oval have been shown to cause of-great circle deflections. A future study could evaluate the magnitude of auroral oval deflections expected for different transmitter locations, propagation directions, and levels of geomagnetic activity. Future work could also address bistatic or multistatic signal paths, or evaluate the occurrence of deflections statistically with angle of arrival measurements from a high latitude HF radio link.
2.A Spring and Fall Figures

Below are figures showing signal power versus frequency and azimuthal shift, and maps of characteristic azimuthal shift for 20 March 2020, and 22 September 2020.

![Figure 2.A1. Received signal power versus frequency and transmitted azimuthal shift from the GCH for rays transmitted from Ottawa. From the top down, rows of panels show received signal power for rays transmitted through an E-CHAIC ionosphere generated for 20 March 2020 at (top) 00:00, (upper middle) 06:00, (lower middle) 12:00, and (bottom) 18:00 EST. From left to right, columns of panels show received signal power for rays reaching (left) Target 1 (54.4° N, 75.7° W), (middle) Target 2 (63.4° N, 75.7° W), and (right) Target 3 (72.4° N, 75.7° W).]
Figure 2.A2. Received signal power versus frequency and transmitted azimuthal shift from the GCH for rays transmitted from Ottawa. From the top down, rows of panels show received signal power for rays transmitted through an E-CHAiM ionosphere generated for 22 September 2020 at (top) 00:00, (upper middle) 06:00, (lower middle) 12:00, and (bottom) 18:00 EST. From left to right, columns of panels show received signal power for rays reaching (left) Target 1 (54.4° N, 75.7° W), (middle) Target 2 (63.4° N, 75.7° W), and (right) Target 3 (72.4° N, 75.7° W).
Figure 2.A3. Maps of expected characteristic transmitted azimuthal shift for propagation from Ottawa (left) and modeled ionospheric critical frequency from E-CHAIM (right) for four times on 20 March 2020. From the top down, maps show characteristic azimuthal shift and critical frequency for 05:00 UT (local midnight), 11:00 UT (hour closest to local sunrise), 17:00 UT (local noon), and 23:00 UT (hour closest to local sunset). Thick black lines on each map indicate the position and orientation of the solar terminator at the corresponding time.
Figure 2.A4. Maps of expected characteristic transmitted azimuthal shift for propagation from Ottawa (left) and modeled ionospheric critical frequency from E-CHAIM (right) for four times on 22 September 2020. From the top down, maps show characteristic azimuthal shift and critical frequency for 05:00 UT (local midnight), 11:00 UT (hour closest to local sunrise), 17:00 UT (local noon), and 23:00 UT (hour closest to local sunset). Thick black lines on each map indicate the position and orientation of the solar terminator at the corresponding time.
HF radio wave signals experience absorption when passing through the D and lower E regions of the ionosphere. When space weather phenomena increase ionization in these regions, the resulting absorption can significantly reduce received signal power, or even prevent signals from being received at all. Typically, ionospheric absorption models characterize the absorption expected at 30 MHz. Absorption \( A_{f_1} \) at a given frequency \( f_1 \) is scaled to other frequencies \( f \) using a simplified power-law relationship

\[
A_f = \left( \frac{f}{f_1} \right)^n A_{f_1},
\]

where \( n = -2 \). This is based on simplification of the Appleton-Hartree equation.

Fiori et al. (2023) explores the relationship between absorption and frequency using multi-frequency (10-80 MHz) absorption data from the Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA) for 13-14 November 2012.

In Year 2, the initial relationship developed in Year 1 was scrutinized by thoroughly cleaning the KAIRA riometer data to reduce noise. KAIRA includes a low-band antenna array for riometry consisting of 48 cross-dipole antennas dispersed across a field 24 m in diameter. The antennas create a 244 beamlet array, where a single beamlet equals to one pointing direction at one frequency. During the period studied, all the receiver beamlets pointed along the zenith direction and collected data for 244 frequencies distributed between 9.765625 MHz and 81.0546875 MHz at a 1-second resolution. Frequency resolution was 0.391 MHz, except for the range 33.59375 to 57.2265625 MHz where it dropped to 0.195 MHz.

Data for 13-14 November 2012 were considered (Figure 3.1a) and filtered as follows:

- Data were downsampled to a 1-minute resolution.
- Absorption values < 0.2 dB were discarded as unreliable due to errors associated with baselining the absorption data.
- Spikes were removed by performing a boxcar smoothing with a smoothing window of 3 minutes and rejecting data more than two standard deviations from the smoothed curve.
- To ensure a range of data was available for constraining the absorption frequency relationship, data in each minute were required to have good absorption data from at least 50 frequencies over a frequency range of at least 20 MHz.

Filtering reduced the data set to 627 one-minute intervals (Figure 3.1b). Notably, the broad range of values spanning the majority of 13 November 2012 were removed as the
data are patchy and appear to be contaminated by noise. Results presented in Fiori et al. (2023) have been updated based on the filtered data set. What follows is a summary of the work and a presentation of the new Figures.

The KAIRA data were first examined to estimate the coefficient \( n \) from the equation above. The coefficient in a power law relationship is characterized by a straight line in a log-log plot, where the value of the slope is the value of the coefficient. The coefficient \( n \) is then given by the best-fit line relating \( \log(A) \) to \( \log(f) \), where \( A \) represents absorption derived from the KAIRA data and \( f \) is the corresponding frequency in MHz. A coefficient was separately determined for each of the 627 1-minute intervals. Figure 3.2a presents the Pearson correlation coefficient of the data, and Figure 3.2b presents the power law exponent \( n \) which peaks at -1.85, deviating from the \( n=-2 \) prediction.

Dependencies in the power law exponent were evaluated. In Figure 3.3a, \( n \) is plotted against absorption at 30 MHz each minute. The scatter in \( n \) is largest for low (<0.5 dB) absorption at 30 MHz. Both the upper and lower boundary of the scatter envelop narrow toward the distribution peak of -1.85 as absorption increases. Figure 3.3b plots \( n \) as a function of hour. The lowest values and largest variation in \( n \) are observed in hours 29-35, corresponding to 05-11 UT (08-14 LT) on 14 November 2012. During this interval the data show less correlation than for other periods, especially for frequencies < 15 MHz. On this day, local sunrise and sunset are 08:19 LT and 12:24 LT respectively, and the largest variation is therefore observed on the dayside where data at lower frequencies are more likely to be absorbed.
Figure 3.2. (a) Distribution of the Pearson correlation coefficient (R) relating log(A_data) and log(f). (b) Power law exponent n from describing the absorption frequency relationship. Both figures are based on the 627 absorption and frequency data for 13-14 November 2012 where data met quality requirements.

Figure 3.3. Power law exponent n, determined as the best-fit line relating log(A_data) and log(f) for 13-14 November 2012 by the KAIRA system. (a) n versus the absorption at 30 MHz. (b) n versus hour within the 48-hour period considered. Only data for the 627 one-minute intervals considered in this study are shown.
Following the procedures of Fiori et al. (2023), the absorption frequency relationship was further evaluated using additional techniques to reduce noise contamination. At each time interval $A_{30}$ was evaluated. Examples are shown in Figure 3.4 for the 0.5-0.6 dB, 1.0-1.1 dB, 1.5-1.6, and 2.0-2.1 dB bins. Data plotted in red were filtered out with additional constraints to further eliminate noise contamination.

For each $A_{30}$ bin, including the four examples in Figure 3.4, the good quality (black points) data were fit with a best-fit line given by

$$\log_{10} A = n_{30} \log_{10} f + b_{30},$$

(11)

where $n_{30}$ and $b_{30}$ represent the slope and intercept of the best-fit line for the $A_{30}$ bin, respectively. Variable $n_{30}$ is analogous to the power law coefficient $n$ above, but is specified for each value of $A_{30}$. Figure 3.5 plots $n_{30}$ and $b_{30}$ as a function of $A_{30}$. Slope $n_{30}$ increases linearly as a function of $\log_{10}(A_{30})$; the Pearson correlation coefficient is $R=0.89$. Correlation is somewhat reduced at $R=0.55$ for $b_{30}$, and a linear trend is not as obvious.

Figure 3.4. Absorption derived from KAIRA for frequencies ranging from 10 to 80 MHz. Data are binned based on the absorption at 30 MHz corresponding to each minute of data. Examples are shown for times where absorption at 30 MHz is (a) 0.5-0.6 dB, (b) 1.0-1.1 dB, (c) 1.5-1.6 dB, and (d) 2.0-2.1 dB. Frequencies of 20 and 60 MHz are marked by vertical dashed lines. A frequency of 30 MHz is marked by the solid vertical line. Data are fit by a best-fit line. Red points denote noise and were not considered in this fit.
The mean intercept is 2.44. Following the trends demonstrated in Figure 3.4, \( n_{30} \) steadily increases from -1.95 for \( A_{30} = 0.2 \) dB to -1.40 for \( A_{30} = 2.2 \) dB. Instead of assuming a constant relationship of \( n = -2 \), the results of Figure 3.5 suggest that both \( n_{30} \) and likely \( b_{30} \), change as a function of \( A_{30} \). The equations describing these linear relationships, calculated using a robust least absolute deviation method, are given by

\[
    n_{30} = -1.66 + 0.43 \log_{10}(A_{30}) , \quad \text{and}
\]

\[
    b_{30} = 2.42 + 0.30 \log_{10}(A_{30}) .
\]

The above three equations define a new model for absorption expected at any frequency based on the overall absorption level, here characterized by \( A_{30} \) for data collected by the KAIRA HF system.

Figure 3.5. Intercept \( (b_{30}) \) and slope \( (n_{30}) \) of the best-fit lines to plots of absorption versus frequency in a log-log space where data are binned according to the absorption at 30 MHz. Red lines are expressed by equation (6) for the slope and equation (7) for the intercept.
The absorption–frequency relationship was evaluated by modeling absorption at all frequencies based on the absorption at 30 MHz and then comparing the modelled values against the KAIRA data. Three models were evaluated:

- **Model 1:** The $n=2$ power law relationship derived from the Appleton-Hartree relationship.
- **Model 2:** The model described by the three above equations.
- **Model 3:** Incorporating instrument effects that alter the power law relationship and fitting the data directly to $\log_{10} A = x_1 f + x_2$, where $x_1$ and $x_2$ are the slope and best-fit line to the data.

Model performance is summed up by prediction efficiency, as plotted in Figure 3.6.

In summary, this work examines the relationship between frequency and absorption both derived from the Appleton-Hartree relationships and through an examination of data from the KAIRA multi-frequency riometer. Such a relationship is necessary to scale the absorption derived from measurements or a model at one frequency, typically 30 MHz, to lower frequencies more commonly used for high frequency communications.

Simplification of the Appleton-Hartree equation predicts a power law expression $A \propto f^n$ where $A$ is absorption, $f$ is frequency, and $n=-2$. Several studies confirm this relationship, but report $n$ ranging from -0.8 to -2.4. Based on an event study using data for 13-14 November 2012 from the KAIRA HF system, the theoretical expression was shown to perform reasonably when the overall absorption level, characterized by absorption at 30 MHz ($A_{30}$) was $< 1$ dB. For absorption $> 2$ dB prediction efficiency of the model dropped below 0.5.

The power law expression was examined by individually determining the coefficient $n$ for each minute of the two-day period where data were of good quality. The coefficient was shown to vary as a function of overall absorption level, characterized by absorption at 30 MHz ($A_{30}$). Model performance improved over the $n=-2$ power law expression when...
incorporating a dependence on absorption. Prediction efficiency improved overall and did not drop below 0.5 until $A_{30}$ exceeded ~1.5 dB, a marked improvement over the $n=2$ model.

Deviation from theory is attributed to ambient electromagnetic noise contributions. Since instrument effects are not incorporated into theoretical expressions of absorption, deviation from the $n=2$ relationship predicted by theory is not surprising. A third absorption – frequency scaling model was created where $\log_{10} A \propto f$, and coefficients in the relationship are dependent on $A_{30}$. The new model was shown to accurately predict absorption.
4. Summary of Resolute Bay HF Transmitter Installation

This installation is a rebuild of the original HF transmitter at Resolute, installed as part of the NRCan HF network. In October 2022, the original transmitter was destroyed in a fire after a break-in, resulting in destruction of the transmitter electronics and parts of the antenna. Redevelopment of the Resolute Bay Incoherent Scatter Radar (RISR) site required relocation of the antenna and support electronics. As the guest instrument building was destroyed in the fire, the electronics, antenna, and their housing needed to be installed at the RISR site at a new location. To meet these requirements, a modified shipping container was used to house the transmitter electronics and support equipment. The container was partially framed out, and refitted with electrical, lighting, and temperature-controlled cooling and heating. An interior view of the completed installation can be seen in Figure 4.1. An exterior view, with visible power and network connections to the RISR support buildings, can be seen in Figure 4.2.

Figure 4.1. The Resolute transmitter interior. The transmitter electronics and control computer are in the large rack in the right of the picture. The power backup system is affixed to the wall in white, with the battery bank below it.
Current operations at the RISR host facility are scheduled on a two-week on, two-week off schedule. As a result, the HF transmitter only receives power on a two-week on, two-week-off schedule. To extend the operational timeframe of the transmitter antenna, a significant battery backup system was installed. A 30 kWh lithium ion battery bank and inverter were used for this, allowing for one week of continuous additional operation of the transmitter. This should provide approximately 75% transmitter uptime of the transmitter during limited RISR operations. Currently, RISR is anticipated to resume continuous operations by the end of 2025.

After initial installation of the antenna and transmitter electronics, high standing wave ratio (SWR) values were detected for lower frequencies. SWR is a measure of an antenna’s ability to effectively transmit power. To reduce the SWR and improve transmission, different grounding configurations were tested for the antenna, linear amplifier, and transceiver. The best configuration was found to be using the RISR ground plane instead of the installed RF ground, though lower transmission frequencies still exhibited high SWR. The transmission schedule of the Resolute transmitter was modified to exclude the 4.6 and 7.0 MHz transmissions until a better RF grounding plane can be installed.
5. References


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**DOCUMENT CONTROL DATA**

*Security markings for the title, authors, abstract and keywords must be entered when the document is sensitive*

1. ORIGINATOR (Name and address of the organization preparing the document. A DRDC Centre sponsoring a contractor's report, or tasking agency, is entered in Section 8.)

   Canadian Hazards Information Service
   Hazards Adaptations Operations Branch
   Lands and Minerals Sector
   Natural Resources Canada
   2617 Anderson Road
   Ottawa, Ontario
   K1A 0E7

2a. SECURITY MARKING
   (Overall security marking of the document including special supplemental markings if applicable.)

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2b. CONTROLLED GOODS
   NON-CONTROLLED GOODS
   DMC A

3. TITLE (The document title and sub-title as indicated on the title page.)


4. AUTHORS (Last name, followed by initials – ranks, titles, etc., not to be used)

   Cameron, T.G.; Fiori, R.A.D.; Reiter, K.

5. DATE OF PUBLICATION
   (Month and year of publication of document.)

   November 2023

6a. NO. OF PAGES
   (Total pages, including Annexes, excluding DCD, covering and verso pages.)

   74

6b. NO. OF REFS
   (Total references cited.)

   84

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.)

   Contract Report

8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.)

   DRDC – Centre for Operational Research and Analysis
   Defence Research and Development Canada
   Carling Campus, 60 Moodie Drive, Building 7S.2
   Ottawa, Ontario K1A 0K2
   Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)

   Surveillance, Intelligence and Interdiction

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

   NRCan Space Weather Effects on DND Assets and Operations

10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)

   DRDC-RDDC-2024-C049

10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

   TPA 03-2023

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

   Public release

11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

   Space Weather Effects; Absorption; OTHR; Polar OTHR

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13a. ABSTRACT (when available in the document, the English version of the abstract must be included here.)

High frequency (HF) radio waves can propagate up to thousands of kilometres via reflections between the ground and the ionosphere. This property of HF radio is used by over-the-horizon radar (OTHR) for long-distance surveillance. However, space weather phenomena can impede the operation of OTHR in different ways. For example, horizontal electron density gradients in the F-region ionosphere can deflect radio waves to off-great circle paths, leading to errors in positioning, while enhanced D-region electron density can cause increased absorption of HF radio waves, reducing the range of frequencies usable by OTHR. It is important that space weather impacts to HF radio wave propagation are understood, so that impacts to OTHR can be mitigated as much as possible.

This report summarizes work done in the first half of the 2023-2024 fiscal year toward better understanding space weather impacts to HF radio wave propagation. Research into off-great circle propagation statistics in the polar cap, diurnal off-great circle propagation caused by the solar-terminator, and the frequency dependence of D-region absorption is described. Then, the installation of a re-built HF transmitter at Resolute Bay, Canada meant to help monitor HF radio wave propagation conditions is described.

13b. RÉSUMÉ (when available in the document, the French version of the abstract must be included here.)

Les ondes radio de hautes fréquences (HF) peuvent propager jusqu'à milliers de kilomètres via les réflexions entre le sol et l'ionosphère. Cette propriété des radios HF est utilisée par le radar transhorizon (OTHR) pour la surveillance à distance. Cependant, les phénomènes météorologiques spatiaux peuvent empêcher l'opération de OTHR de nombreuses façons. Par exemple, l'inclinaison de la densité électronique horizontale dans la région F de l'ionosphère peut dévier les ondes radio aux chemins hors du grand cercle, qui entraînera des erreurs de positionnement, lorsque la densité électronique augmentée de la région peut causer plus de l'absorption des ondes radio HF, qui réduira la bande de fréquences utilisable par OTHR. C'est important que les impacts de météorologie spatiale aux ondes radio HF soient compris, afin que les impacts à l'OTHR soient atténués le plus que possible.

Ce rapport résume le travail accompli dans le premier demi de l'année fiscale 2023-2024 pour mieux comprendre les impacts météorologiques spatiaux à la propagation des ondes radio HF. La recherche sur les statistiques de la propagation hors du grand cercle dans la calotte polaire, la propagation hors du grand cercle causée par le terminator solaire et la dépendance en fréquence de la région D est décrite. Ensuite, l'installation d'un émetteur HF reconstruit à Resolute Bay, Canada pour aider à surveiller les conditions pour la propagation des ondes radio est décrite.